NATURAL CONVECTION FROM A HELICAL HEATING COIL TO THE SURROUNDING FLUID

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Abstract An experimental study is reported on natural convection heat transfer from a helical heating coil to the surrounding fluid. The coil is heated electrically and the surrounding fluid is selected to be water. The range of parameters are: Rayleigh number, $879 \leq Ra \leq 780168$, Prandtl number, $4.22 \leq Pr \leq 10.02$, dimensionless coil diameter, $7.69 \leq D_{ave}/d \leq 10.77$, number of coil rings, $2 \leq N \leq 8$, and the dimensionless coil pitch $l/d= 1$. The results are correlated by means of a modified Nusselt number. The proposed correlation is a convenient tool for estimating heat transfer from helical coils.

Key Words Natural Convection, Free Convection, Heat Transfer, Helical Coil

چکیده در این بررسی تجربی، انتقال حرارت جابجایی آزاد از یک کویل گرمازا اندازه گیری شده است. کویل به وسیله جریان برق گرم می شود و سیال اطراف آن آب است. آزمایش در گستره عدد ریلی ۸۷۹ ≤ Ra≤ ۷۸۰۱۶۸، عدد پرانتل ۴/۲۲ ≤Pr≤ ۱۰/۰۲، قطر بی بعد کویل ۷/۶۹≤ Dave/d≤ ۱۰/۷۷، تعداد حلقه های کویل ۲≤N≤۸ و گام بی بعد کویل l/d=۱ انجام شده است. نتایج به دست آمده نشان می دهد که عدد نوسلت اصلاح شده، رابطه مناسبی به دست می دهد. رابطه ارائه شده در این مقاله وسیله مناسبی برای برآورد انتقال حرارت از کویلهای گرمازاست.

INTRODUCTION

This paper reports the results of an experiment concerned with natural convection heat transfer from a helical heating coil to the surrounding fluid. The main objective is to measure heat transfer coefficient for the external surface of the coil and to present the results in the form of convenient correlations for practitioners.

The schematic representation of a typical coil used in this study is given in Figure 1. As heat is generated within the coil by electrical power, the temperature of the coil surface increases. As a result, the surrounding fluid becomes less dense and the buoyancy forces induce a natural convection process. With this arrangement, the fluid at the central core of the coil will experience a chimney effect which drives the fluid up through the coil. However, the spacings between the coil rings permit the infiltration of fluid into the central core and thus reduce the chimney effect.

Another noteworthy feature of natural convection around a helical coil is the swirling motion generated by the helical geometry of the coil. This swirl, which is caused by the sloped coil rings, disturbs the otherwise axisymmetric flow around the coil. In fact, the flow field is three dimensional. Further, the vortices shed by each of the rings is intercepted by the neighboring rings situated above. The presence of these flow features generate a very complex flow field which has a significant effect on heat transfer.

The heating coil has many practical applications. It is often used in refineries and power stations to keep heavy fuels at an elevated temperature during the winter so that the fuel flows easily in the passages. It is also used in hot water tanks as a submerged heat exchanger, or in tank heating in arctic merchant vessels. In a search of literature, the authors used a computerized data bank which contained 63912 papers on heat transfer with 5588 on natural convection. When the search was narrowed down to the coil problem, only 13 papers were identified to have the keyword "coil". Most of these papers were concerned with electrical coils or, in the case of heat transfer, laminar flow inside the helically-coiled tubes (Patankar et al., 1974), which did not contribute to the present investigation. So, despite the practical importance of heating coils, it appears that the problem has not been paid the due attention by the researchers.

A closely related problem, which may be employed to estimate heat transfer from helical coils, is natural convection from horizontal cylinders. Heat transfer from cylinders is extensively discussed by Morgan (1975). Morgan has presented correlations based on a large collection of experimental results from the literature. Other related works are heat transfer from arrays of horizontal cylinders (Masters, 1972) and natural convection from thin wires (Molki and Etemad, 1990). Estimates based on cylinder correlations may not be sufficient for certain design problems. The present work is an attempt to provide correlations which are directly applicable to helical heating coils.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup consists of a water tank, five helical coil heaters, and the necessary instruments. The water tank has a cylindrical geometry (height = 1.2 m and diameter =1.3 m) made of 1.5 mm galvanized iron sheet. For the experiments, the tank was filled with water and the helical coil was immersed in it and held in position with threads and hooks to the rim of the tank. The necessary adjustments were made to keep the coil in a vertical position.

A typical coil is shown in Figure 1. The coils were made of copper tubes to reduce temperature gradient along the coil rings. Resistor wires were implanted in the copper tubes for heating purposes. A total of five coils were used in this investigation. The dimensions of the test coils are given in Table 1. The coil surface temperature was measured by copper-constantan thermocouples with 0.3 mm diameter lead wires. The thermocouples were soldered to the surface at three different spots along the coil.

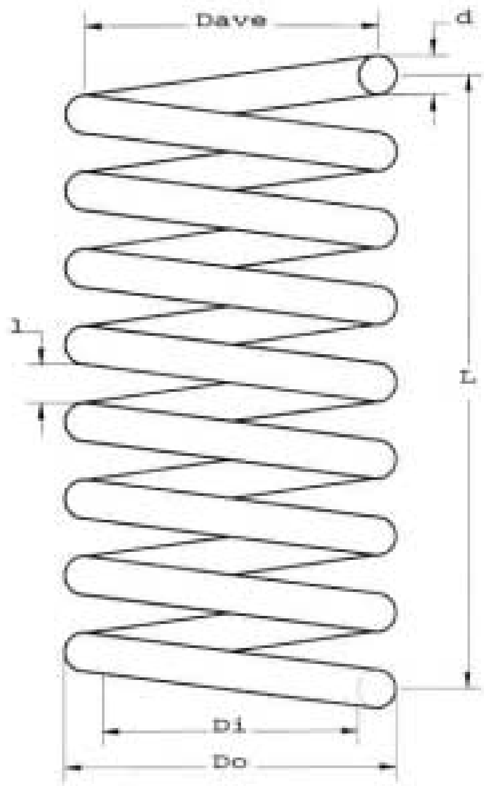

Figure 1. The helical coil used in this study (coil number 3 in Table 1).

The electrical circuit of the experimental setup is shown in Figure 2. This circuit is so designed that the power supplied to the test coil would not be interrupted while the voltage or current is being recorded. In this figure, E and R are the voltage supplied and the resistance of the coil heating wires respectively. There are three control switches identified with S1, S2 and S3. If closed and open positions of switches are identified with (S1, S2, S3) = (1, 1, 1) and (0, 0, 0), then the setup is marked with (S1, S2, S3) = (0, 0,

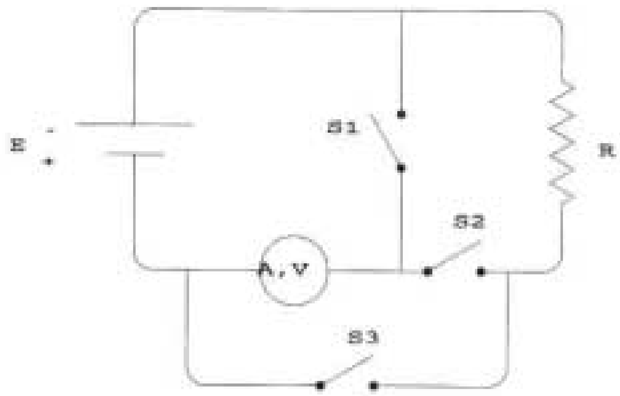

Figure 2. The electrical circuit.

1) during the normal operating condition, (S1, S2, S3) = (1, 0, 1) during voltage measurement, and (S1, S2, S3) = (0, 1, 1) and then (0, 1, 0) during current measurement.

The voltage and current measurements were performed with a precision multimeter (Philips, PM 2525) which could resolve voltage to 0.001 mV. The electrical power was provided by a DC power supply (Philips, PE 1646) with voltage and current ranging from 0 to 75 V and 0 to 6 A.

In a typical data run, the control switches S1, S2, and S3 (Figure 2) are placed on 1 position, and the power supply is turned on. The voltage of the coil resistor is adjusted to a pre-determined value and kept until the system reaches a steady state. To ensure that the steady state had been reached, these parameters are recorded during the warmup period: current, voltage difference across the coil resistor, and *emf* of the thermocouples. Once the values of these parameters are stabilized, and the steady state has been reached, these additional parameters are measured: reference temperature of the thermocouples and water temperature. The experiments are repeated for five test coils.

DATA REDUCTION

The power provided to the coil is calculated from W = VI, where V is voltage across the coil and I is the current. Part of this power is dissipated to the surroundings by thermal radiation. If the radiative component of heat transfer is not separated from the convective component, the heat transfer coefficient may be defined as $h = Q / (A\ \Delta T)$, where $Q = W$ and $\Delta T = T_s - T_\infty$. In these equations, T_s is the average of the three thermocouple readings, and A is the surface area of the coil in contact with water. The heat transfer coefficient is subsequently written in terms of Nusselt number, Nu=hd/k, based on the coil copper-tube diameter.

In buoyancy-driven flows, the heat transfer coefficient is often expressed as Nu=f(Ra, Pr). In this expression, Ra is the Rayleigh number defined as $Ra = (g\beta\Delta T d^3)/\upsilon\alpha$, and the Prandtl number is $Pr = \upsilon/\alpha$. In the next section, the heat transfer results will be presented in terms of Ra number, and it will be seen that the effect of Pr is insignificant in the present work.

RESULTS AND DISCUSSION

Figure 3 presents the heat transfer coefficients for the coils numbered 1 to 3. The abscissa is Ra number as defined earlier, and the ordinate is Nu number. The results show a linear variation of Nu with Ra on a logarithmic scale, so a curve fit of the form $Nu = mRa^n$ seems appropriate. With this correlation, the least-squares fit to the data are,

$Nu = 0.320\ Ra^{0.262}$ coil no 1, Figure 3a (1)

$Nu = 0.189\ Ra^{0.298}$ coil no 2, Figure 3b (2)

$Nu = 0.305 Ra^{0.276}$ coil no 3, Figure 3c (3)

The standard deviations of data from these correlations are 0.098, 0.064, and 0.083, respectively. If the uncertainty or goodness of fit is defined as (2 × standard deviation × 100)/(mean Nu), it may be

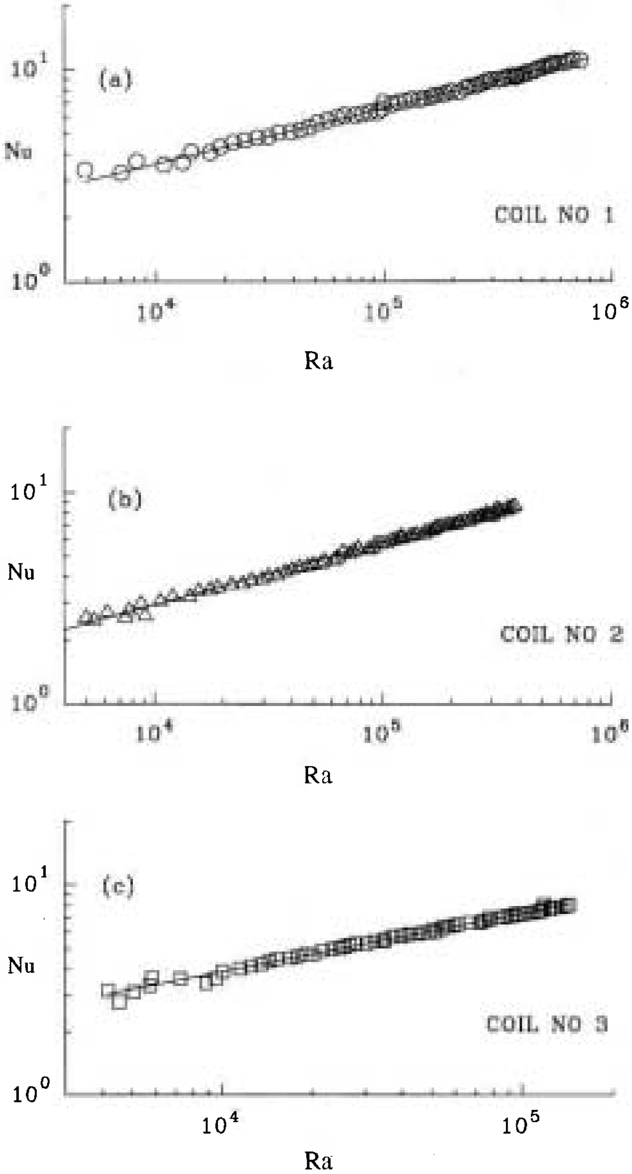

Figure 3. Variation of Nusselt number for **(a)** coil No 1; **(b)** coil No 2; **(c)** coil No 3.

concluded that Equations (1) - (3) are good to within ±2.6%, ±2.2%, and ±2.7%, respectively. The data scatter seen at lower Ra is due to the larger experimental uncertainty when the power supply operates at lower powers.

Similar data are reported for coils 4 and 5 in Figure 4. As seen in Table 1, these coils are shorter and have larger diameters. The trend is similar to the earlier graphs and they may be represented with the following equations,

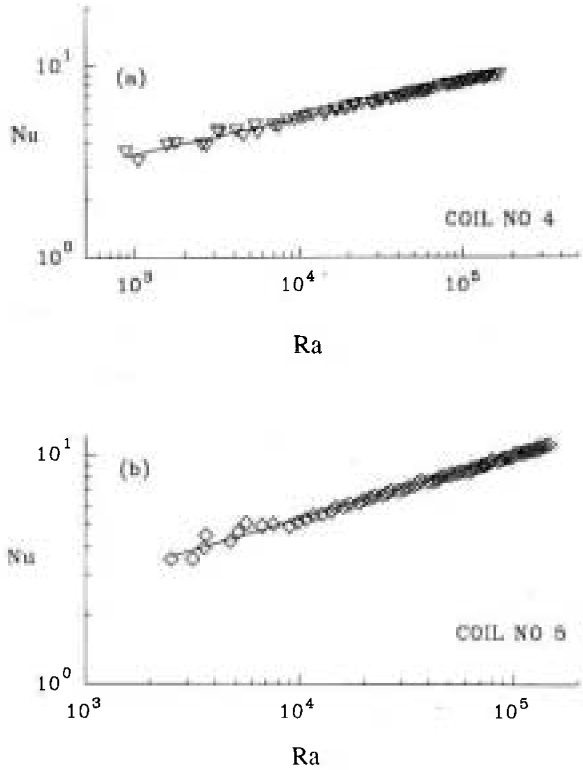

Figure 4. Variation of Nusselt number for **(a)** coil no 4; **(b)** coil no 5.

TABLE 1. Coil Dimensions.

Coil No.	N	L, cm	l, cm	d, cm	D_{ave}
1	2	3.06	0.77	0.77	5.92
2	4	6.13	0.77	0.77	5.92
3	8	12.26	0.77	0.77	5.92
4	2.18	3.80	0.95	0.95	8.29
5	4	6.13	0.77	0.77	8.29

$$Nu = 0.928Ra^{0.190} \quad \text{coil no 4, Figure 4a} \quad (4)$$

$$Nu = 0.413Ra^{0277} \quad \text{coil no 5, Figure 4b} \quad (5)$$

The standard deviations of data from these correlations are 0.083 and 0.101, with the equations being good to within ±2.5% and ±2.6%, respectively.

The aforementioned results were obtained for a narrow range of Prandtl number. The effect of Pr on

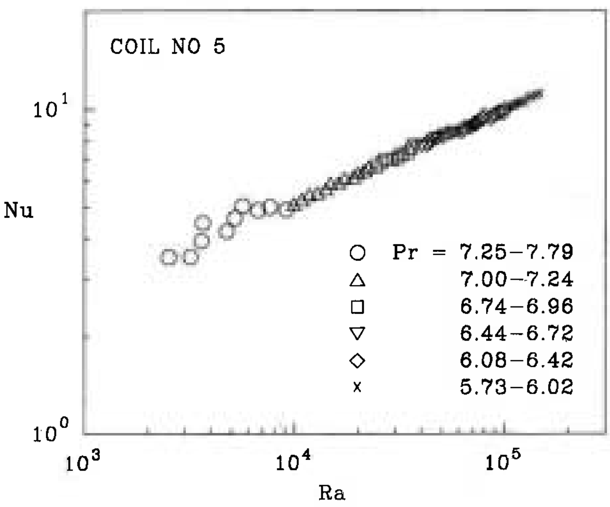

Figure 5. Effect of Pr on Nu distribution.

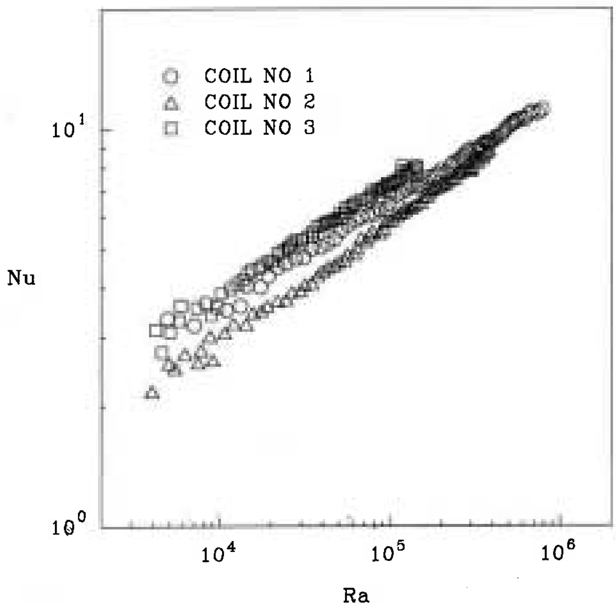

Figure 6. Variation of Nusselt number for coils 1,2, and 3.

Nu is investigated in Figure 5, where the data are presented in six groups. In each group, the Pr variation is much smaller than the overall range of Pr. It is seen that the data follow the same trend and the effect of Pr is apparently insignificant.

The initial understanding of heat transfer in buoyancy-induced flows is described by Nu = f(Ga, Pr), where Gr is the so-called Grashof number (Gr = Ra/Pr). This was later modified as Nu = f(Ra, Pr). In more recent studies, the heat transfer coefficients are correlated as Nu= $f[Ra/(1 + Pr^{-1})]$ with $Ra/(1 + Pr^{-1})$ being the fundamental dimensionless number characterizing the buoyancy-induced flows (Arpaci and Bayazitoglu, 1990). This latter correlation approaches RaPr for liquid metals (very small Pr) and simplifies to Ra for heavy oils (larger Pr). In the present investigation, the coils were tested in water with $4.22 \leq Pr \leq 10.02$. However, based on the results presented in Figure 5, the effect of Pr on the heat transfer coefficient of the helical coils seems to be negligible. This is especially true when the coil is used for heating heavy fuels.

The heat transfer results for coils 1 to 3 are brought together in Figure 6. In general, the results may be described as Nu= f(Ra, Pr, Geometry). The geometry of the helical coil is identified with D_{ave}/d, 1/d, and N. In this study, 1/d was equal to one for all the experiments (see Table 1). To correlate the data, a modified Nusselt number is defined as,

$$Nu^{+}=Nu/(0.431 - 5.132 \times 10^{-2}N + 5.888 \times 10^{-3}N^{2}) \quad (6)$$

With this definition, the results of Figure 6 are correlated as

$$Nu^{+}= 0.766Ra^{0.277} \quad \text{coils 1, 2, and 3, Figure 7} \quad (7)$$

and presented in Figure 7. The standard deviation of data from Equation 7 is 0.291 and the equation is good to within ±3.2%.

A similar curve-fitting procedure was applied to the data for coils 4 and 5 (Figure 8). In this case, the modified Nu is defined as,

$$Nu^{+}=Nu/(3.054 - 1.783NRa^{-0.039N}) \quad (8)$$

and the data are correlated as,

$$Nu^{+}= 1.352Ra^{0.117} \quad (9)$$

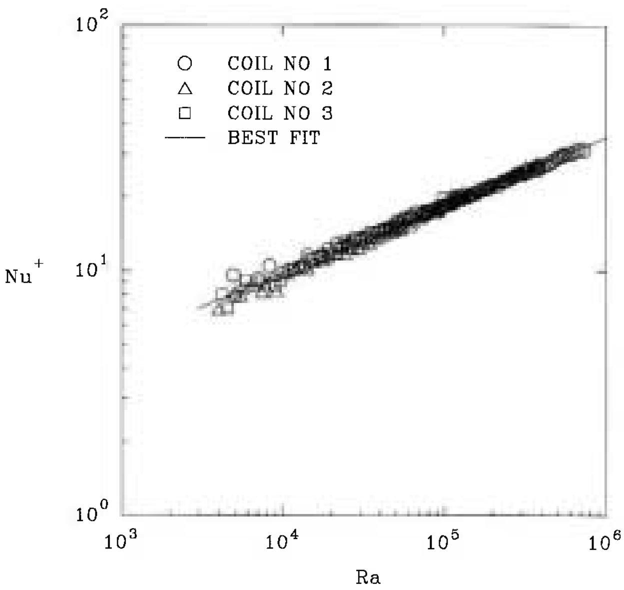

Figure 7. Modified Nusselt number for coils 1, 2, and 3.

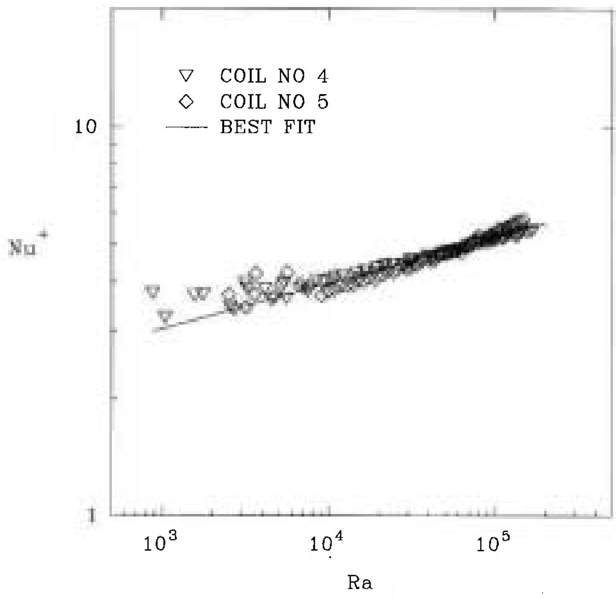

Figure 8. Modified Nusselt number for coils 4 and 5.

The standard deviation of data from this equation is 0.126 and the equation is good to within ±5.5%.

In a final attempt to bring all the data together and to present a general correlation, the Nu number was modified as,

$$Nu^{+}=Nu/(mRa^{n}) \quad (10)$$

$$m= (0.947 - 0.179N + 1.228 \times 10^{-2}N^{2})(0.732 + 7.815 \times 10^{-3}D_{ave}/d)$$

$$n = (3.622 \times 10^{-2}N + 2.604 \times 10^{-2}D_{ave}/d - 3.098 \times 10^{-3}ND_{ave}/d)$$

The modified Nusselt number may now be curve fitted to obtain,

$$Nu^{+}= 1.067Ra^{-0.006} \quad (11)$$

Equation 11 is based on 343 data points. The standard deviation of data from the equation is 0.043, and the equation is good to within ±8.6%. This correlation, which is the final outcome of the present investigation, is applicable in the range of parameters considered in this research. In this connection, Ra ranged from 879 to 780168, D_{ave}/d from 7.69 to 10.77, and N from 2 to 8 with l/d = 1. The effect of Pr for water and more viscous fluids is apparently negligible.

CONCLUDING REMARKS

An experimental study was reported on measure-

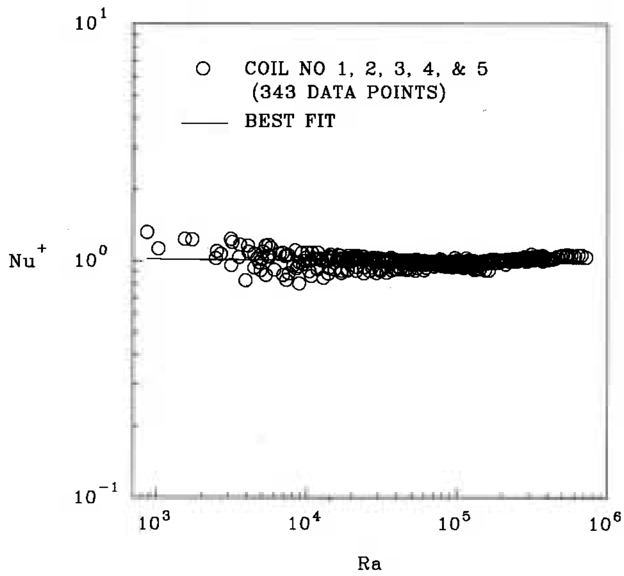

Figure 9. Modified Nusselt number for all data.

ment of convective heat transfer coefficient from a helical heating coil. The coil was oriented in vertical position and the experiments were carried out in water.

The results indicate that Nu depends strongly on Ra, while the effect of Pr appears to be negligible. The data were successfully correlated using a modified Nusselt number and the least-squares curve fitting procedure. The final correlation includes the effect of Ra as well as those of the geometrical parameters of the coil. The presented correlations are limited to the range of parameters considered in this investigation.

NOMENCLATURE

A	surface area of the coil in contact with water
D_{ave}	mean diameter of the coil, Figure 1
l	coil pitch, Figure 1
d	diameter of the coil copper-tube, Figure 1
Gr	Grashof number, Gr = Ra/Pr
h	heat transfer coefficient, $\dot{Q} / (A \Delta T)$
I	electrical current
k	thermal conductivity, w/(m K)
N	number of coil rings
Nu	Nusselt number, hd/k
Pr	Prandtl number, υ/α
$\dot{Q}$	rate of heat transfer by convection and radiation
Ra	Rayleigh number, $(g\beta\Delta T d^3)/\upsilon\alpha$
T_s	coil surface temperature
T_∞	temperature of the surrounding fluid
V	voltage
W	power provided to the coil by the power supply, VI

Greek Symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, K^{-1}
μ	viscosity, N s/m^2
υ	kinematic viscosity, m^2/s
ρ	density, kg/m^3

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