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Study of Heat Transfer from a Sphere Body to Flowing Media

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Abstract

In the present research the convective heat transfer from a hollow copper sphere (10.2 cm in diameter) to air is studied at different temperatures of sphere surface. The experiments were carried-out in an experimental channel (245 x 48 x 50 cm) and the velocity of air was changed by varying the orientation of the gate of the channel which has four levels. A fan of moderate capacity generates air into the channel.

The sphere was heated by hot water at approximately constant wall at different measured temperatures 40, 50, 60, 70 and 80 ^{0}C and local heat transfer coefficients were calculated. This process was done by placing ten thermocouples into the inner surface of sphere. These thermocouples were connected to a digital reader which gives the instantaneous temperature of a specified region. The thermocouples were numbered and distributed in an equal angular displacement of 36 degrees.

The determination of heat transfer coefficient was done through two regions, the first called the front region, which faces the fan, and the second called the wake or backward region in which vortices were generated and built-up. A variance of temperature was recognized between these two regions in such a way that front heat transfer coefficient was higher than that for backward region.

The analysis of the present work is based on Reynolds number which is change from 12894 to 33282 depends on the velocity of the used fan. The experimental results of this study were compared with Kendoush analytical correlation (1995) together with a number of certain other mathematical equations obtained from the literature. It was found that this comparison was good especially at higher temperatures.

دراسة انتقال الحرارة من جسم كروي الى وسط جاري

الخلاصة

يتناول البحث دراسة تأثير انتقال الحرارة بين جسم معدني مصنوع من النحاس على شكل كرة مجوفة قطرها (10.2 سم) وبين الهواء وعند درجات حرارة مختلفة، أجريت التجارب في جهاز خاص يدعى (القناة الصناعية) وهو عبارة عن قناة متغيرة المقطع أبعادها (245 X 48 X 50 سم) حيث تم التحكم بتدفق الهواء الذي يجري الى داخل القناة عن طريق مروحة ذات قدرة متوسطة وتم تغير سرعته عن طريق بوابة دائرية ذات أربع فتحات والتي تحجب الهواء عن المرورالى داخل القناة تدريجيا . تم تسخين الكرة النحاسية بالاعتماد على مبدأ درجة حرارة السطح الثابتة وباستخدام ماء ساخن لمدى من درجات حرارة تتراوح 40 الى 80 درجة مئوية. تم حساب معامل انتقال الحرارة الموقعي عن طريق معرفة درجات الحرارة بواسطة مزدوجات حرارية مثبتة الى داخل سطح الكرة حيث تم زرع عشر مزدوجات حرارية في عشر مواقع متساوية وموزعة بالاتجاه القطري تفصل بين واحدة وأخرى مسافة 36 درجة، ذ ترتبط

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هذه المزدوجات الى مقياس رقمي يعطي القيمة الفعلية لدرجة الحرارة عند الموقع المحدد. تم دراسة انتقال الحرارة خلال منطقتين من الكرة، المنطقة الأولى تدعى المنطقة الأمامية وهي المنطقة الواقعة تحت التأثير المباشر للمروحة و المنطقة الأخرى تدعى المنطقة الخلفية وهي المنطقة التي تتكون فيها الدوامات نتيجة للسرع العالية. تم دراسة التباين في انتقال الحرارة في هاتين المنطقتين ووجد ان كلا من معامل انتقال الحرارة ومعدل انتقال الحرارة في المنطقة الأمامية يكون أعلى من قيمته عند المنطقة الخلفية. اعتمدت الحسابات على رقم رينولدز تتراوح قيمته من 12894 عند أوطأ سرعة للهواء الى 33282 عند أعلى سرعة له وذلك اعتمادا على القدرة التي تزودها المروحة المستخدمة. قورنت النتائج المستحصلة مع بعض البحوث المتوفرة لحساب معدل رقم نسلت (كدالة لرقم رينولدز) وقد كانت النتائج العلمية متقاربة مع بعض العلاقات خصوصا مع معادلة كندوش التحليلية (1995) هذا التقارب الذي يزداد بزيادة درجة الحرارة.

Keywords: Forced Convection, Heat on a Sphere Body, Flowing around spheroids Bodies.

Nomenclature

A_F,	Front cross sectional area of sphere, m ^{2}
A_W,	Wake cross sectional are of sphere, m ^{2}
A_t ,	Total cross sectional are of sphere, m ^{2}
Cp	Specific heat of air or water, J/kg.K
d,	Sphere diameter, m
m^0	Mass flow rate of water, kg/s
R,	Radius of inlet section of duct, m
h_a,	Average heat transfer coefficient,W/m^2. K
h_F,	Heat transfer coefficient for front region of sphere, W/m^2. K
h_W,	Heat transfer coefficient for wake region of sphere, W/m^2. K
h_θ,	Local heat transfer coefficient, W/m^2. K
k,	Thermal conductivity of air, W/m . K
Nu,	Nusselt number (=h d / k), dimensionless
U_∞,	Free stream velocity of air, m/s
U_F,	Velocity of air at the front region of sphere, m/s
U_W,	Velocity of air at the wake region of sphere, m/s
U_{max},	Maximum velocity of air in the duct, m/s
Q,	Total rate of heat transfer, W
Q_F,	Rate of heat transfer to the front region of sphere, W
Q_W,	Rate of heat transfer to the wake region of sphere, W
T_θ,	Local temperature measured by thermocouples, K
T_i ,	Inlet water temperature, K
T_e ,	Exit water temperature, K
T_a,	Average temperature of sphere, K
T_∞,	Temperature of air at free stream, K
W_{m^o},	Uncertainty of water mass flow rate (= ± 0.00055 kg/s)
W_d,	Uncertainty of sphere diameter (= ± 0.5 mm)
$W_{\Delta T}$,	Uncertainty of temperature difference between sphere surface and air (= ± 0.5 ^{0}C)
$W_{\Delta T1}$,	Uncertainty of temperature difference between inlet and outlet water (= ± 0.01 ^{0}C)

Greek Symbols

θ_s, Separation angle measured from FSP of sphere, degrees

Δ_T, Temperature difference between sphere surface and air ($= T_a - T_\infty$), K

Δ_{T1}, Temperature difference between inlet and outlet water ($= T_i - T_e$), K

Abbreviations

FSP, Front stagnation point of sphere

RSP, Rear stagnation point of sphere

HTC, Heat transfer coefficient

Introduction

Although that the study was carried out on a sphere, it is anticipated that the data obtained may be applied as a first approximation to local coefficients on geometrically similar bodies such as parabolas, ellipsoids and other surface of revolution. [John R. Cary 1953].

By concentrating attention on the surface effects, the idea of boundary layer type flow is introduced which enables a simple analysis to be devised. It is well established that there are essentially two regimes of wake flow, the first regime may be described as steady, being characterized by standing vortex ring of axsymmetric shape at the rear of the sphere, this occurs at relatively low flow rates. The second regime beings when an increase in the stream velocity ultimately results in a quasi-steady wake flow of a complex nature: a decrease in the stability of the vortex ring as it grows results in shedding of the vortex, soon after, another vortex is created and this finally detaches with the same fate as its predecessor. [Lee and Barrow 1964].

The convective heat and mass transfer from isothermal spherical particles surrounded by a flowing fluid are involved in many engineering industries. Among these industries are: drying, adsorption, extraction, fixed and fluidized-beds, cooling of airplane components, cooling of spherical-fuel elements in certain types of nuclear reactors. [Rowe P.N. Claxton and Lewis 1965]

There are many engineering systems that are modeled using forced convection, such as electronic components on printed circuit boards placed in cabinets, hot-wire anemometers and heat exchangers design. Many researchers have investigated steady laminar forced convection heat transfer from an isothermal sphere into a substantial amount of air or water experimentally, analytically and numerically for over 90 years. [Gostkowski V.J. and Costello 1970]

Steady, laminar and forced convection experimental heat transfer from isothermal spheres into air streams of large extent can be influenced by many factors such as radiation effects, conduction along supports, wind tunnel blockage and natural convection effects. For must common cases, heat-transfer rates can be adequately predicted from available engineering analysis or correlation. [Yovanovich M.M 1988].

The complicated flow patterns of the fluid in the separated region behind the sphere are not easily handled by conventional analytical methods, as a contribution to the solution of the problem of the sphere wake, experiments have been conducted in the lower velocity range when the flow pattern can be carefully observed. The object of present study is to measure the heat transfer coefficient and then calculate the Nusselt number for the air which crosses the sphere and study the fluid movement on the surface of the sphere and uses the boundary layer theory to give an explanation of the flow pattern in front and behind the sphere.

Also the study is related to the velocity of air and how the flow may change from laminar in front of the sphere to turbulent behind it because of formation of the vortex in the wake region of the sphere.

Theoretical Analysis

A hollow sphere of 10.2 cm made from copper was used in the experimental work. This sphere was subjected to a following air at free-stream condition and the aim is to get the relation between Nusselt and Reynolds numbers in both the front and wake regions of sphere and temperature distribution during the cooling process which takes part in this analysis. Basically the experimental work is the starting point from which other correlations are compared to the data obtained from it. It is clear that the wake region is complex in nature and there is a stagnation point at 180o from a reference point which faces directly the flowing air called rear stagnation point (RSP) and also there is a stagnation point at 0o (reference) called front stagnation point (FSP), It was assumed that the relation of Lee and Barrow (1964) rules the velocity in this region. Generally, the wake region exchanges heat with air and the rate of heat transfer in this region was found to be less than that of the front region and the cooling process takes place under the assumption of constant wall temperature of sphere. The boundary layer formation is initiated at FSP where the fluid is brought to rest with an accompanying rise in pressure. The pressure is maximum at this point and it decreases with increasing axial distance along the sphere (X), the streamline coordinates and angular coordinate. The boundary layer is then said to be developing under the influence of a favorable pressure gradient ($\delta P/\delta X < 0$), however, the pressure must eventually reach a minimum towards the rare of the sphere, further boundary layer development occurs in the presence of adverse pressure gradient (($\delta P/\delta X > 0$)) [Coulson J.M. and Richardsen 1996]

The presence of an adverse pressure gradient complicates flow conditions, its effect is to decelerate the flowing fluid particularly the slower moving particles near the surface and condition is eventually reached for which the velocity gradient at the surface becomes zero. At this location the fluid near the surface lacks sufficient momentum to overcome the pressure gradient and continued downstream movement is impossible. [Coulson J.M. and Richardsen 1996].

Since the momentum of the fluid in a turbulent boundary layer is larger than in the laminar boundary layer, it is reasonable to expect transition to delay the occurrence of separation. If $Re_d < 2 \times 10^5$ (which it is our case study) the boundary layer remains laminar and the separation occurs at $\theta = 80^0$, however if $Re_d > 2 \times 10^5$ the boundary later transition occurs and separation is delayed to $\theta = 140^0$. [Incropera and Dewitt 1996]

The rate of hear transfer from water to the sphere is calculated from:

$$Q = m^0 \, Cp \, \Delta T_1 \qquad (1)$$

The velocity was measured by an instrument known digital micro-manometer and it represents the velocity at the inlet of the experimental channel and the recorded velocity is considered a maximum because it measured at the centerline of the duct. The starting section of the duct is considered pipe and the average velocity is calculated by multiplying the measured maximum velocity by a constant varying from (0.7-0.82) depending on the type of flow and the value of Reynolds number.

Figure (2) represents the relation between (U/Umax) and the Reynolds number which performs the shape of resulting relation.

The wake velocity (sphere back-region velocity) can be calculated by means of relation of Lee and Barrow (1964) as follows:

$$Uw = 0.077 \times U_{\infty} \quad (2)$$

The separation angle (Θs) can be calculated from the correlation of Linton and Sutherland (1960) as follows:

$$\Theta s = 83 + 660\ (Red)^{-1/2} \quad (3)$$

The surface area of the front region of sphere
is calculated from:

$$Af = 4\,\pi\,R^2 \times (2\Theta s/360) \quad (4)$$

Hence, the surface area of the wake region of sphere is calculated from the equation:

$$Aw = At - Af \quad (5)$$

The heat transfer coefficient from the front and wake region of sphere to the flowing air is calculated as follows:

$$hF = (h3 + h6 + h2 + h7 + h8) / 5 \quad (6)$$

$$hw = (h4+h1+h9+ h5+h10) /5 \quad ....(7)$$

The distribution of thermocouples in the inner side of sphere surface is shown in figure (4). The thermocouples are recognized by certain numbers and distributed in such a way that thermocouple no.3 refers to FSP and thermocouple no.4 to RSP and thermocouple no.7 refers to thermocouple with 288^0 from the FSP, etc. The angle between each two neighboring points is 360 for total ten thermocouples used.

The individual heat transfer coefficient is calculated from the following equation:

$$h\theta = Q / (A\mathbf{h}\ (T\theta - T\infty)) \quad (8)$$

The front and wake heat transfer rate, therefore, is calculated using the following two equations:

$$Q\mathbf{F} = h\mathbf{F}\ A\mathbf{F}\ (T\mathbf{aF} - T\infty) \quad (9)$$

$$Q\mathbf{W} = h\mathbf{W}\ A\mathbf{W}\ (Taw - T\infty) \quad (10)$$

The front and wake heat rates together must equal the total rate transferred from water according to the equation:

$$Q = Q\mathbf{F} + Q\mathbf{W} \quad (11)$$

The front and wake Nusselt number can be now easily calculated from:

$$Nu_{\mathbf{F}} = h\mathbf{F}\ d / kf \quad (12)$$

$$Nu_{\mathbf{W}} = h\mathbf{W}\ d / kf \quad (13)$$

kf is the thermal conductivity calculated at so called film temperature.The average heat transfer coefficient and average Nusselt number can be calculated using the following equations:

$$h_a = (h_F + h_w) / 2 \qquad (14)$$

$$Nu_a = h_a d / k_a \qquad (15)$$

In the last equation ka is calculated at the average temperature of the sphere.

In order to get an exact estimation to the calculated parameters an uncertainty analysis is to be carried out. This analysis is based on the assumption of constant wall temperature of sphere. The following differential equation stand for uncertainty in the heat transfer coefficient and it can be applied for both front and wake regions as follows:

$$Wh = \{((\delta h / \delta m^o)\, W\mathbf{m}^o)^2 + ((\delta h / \delta \Delta T)\, W\Delta T)^2 + ((\delta h / \delta \Delta T_1)\, W\Delta T_1)^2 + ((\delta h / \delta d)\, Wd)^2\}^{1/2} \qquad \ldots.(16)$$

Experimental Work

Various pieces of equipment were used in the present work to investigate the variables that are believed to have effects on the process, especially on the rate of heat transfer from front and wake regions of sphere. Thermocouples type K (alumel-chromel) were fixed to the interior surface of the sphere by drilling a fine hole in the surface and placing the junction formed from the contact of the attached poles of thermocouple on it then putting it in contact with sphere surface by using a suitable epoxy resin. The thermocouples were placed at equally 10 angles distributed at 36, 72, 108, 144, 180(RSP), 216, 252, 288, 324 and 360 or 0(FSP) degrees as shown in fig.(4), the sphere was heated by hot water pumps from a hot water supply system at different temperatures starting from 40 to 80 ^{0}C with step of 10 ^{0}C.

After the establishment of stability and steady state the fan of the experimental channel was operated at different speeds so that the flowing air cools the hot sphere.

The measurements were taken after (15-20) minutes. The surface sphere temperatures were recorded through a digital thermometer and input and output temperatures of the flowing air and water are measured also.

The air velocity at the inlet of the channel was measured through a digital micromanometer and this velocity was changed for each run through a controlled damper.

The measured velocity is the maximum velocity indicated at the center-line of the duct and the average-velocity is obtained through a trial and error procedure, finally the volumetric flow rate of outlet water was measured through a suitable volumetric cylinder and watch clock.

Results and Discussions

The results can be divided into three regions, the front heat transfer coefficient, wake heat transfer coefficient and the average heat transfer coefficient. In these items the heat transfer coefficient is function to Reynolds number and the temperature of heating water. The local heat transfer coefficient is also an important parameter and it is function to the circular angle (θ) and the velocity of air into the channel.

In the front region of the sphere the heat transfer is calculated for each velocity of air which is changed at four levels starting from the high to the low one. The results obtained are compared with Kendoush correlation (1995) for Nusselt number. He got expressions for local Nusselt number for both front and wake regions and the average Nusselt number for the total region of sphere. Both front and wake regions occupy 50% from the total surface area of sphere. This fact is always true because the boundaries of the front region depend on the Reynolds number and the range of separation angle formed from FSP of sphere.

For the wake region of sphere the experimental results are to be compared with Kendoush correlation for the wake region. It seems from the relation of wake Nusselt number vs. wake Reynolds number that there is a divergence to Kendoush correlation for all speed flow.

This divergence results from direct effect of front region which reduces the temperature of the wake region during the cooling process making the heat transfer coefficient in this region to be high and therefore the Nusselt number increases.

The second reason for this divergence refers to the velocity of water inside the sphere in that it is somewhat high that makes the heat transfer process in the front region to be effective.

The increasing of temperature relatively improves the convergence to the experimental results especially at higher one.

For the average Nusselt number the experimental results are to be compared to number of correlations that accounts for the average Nusselt number for certain limits.

It was seen that Yovanovich model (1994) applies exactly with Yuge correlation (1960) and the two performs one curve. Kendoush correlation is the closes to the experimental results among all these relations.

The increasing of temperature affects the convergence to other correlations but affects more to that of Kendoush correlation.

The local Nusselt number is calculated at different angular positions measured from the FSP of sphere. These rates give distribution of heat through angular coordinate to locate where the maximum and minimum values occur.

It is possible to use more than one coordinate system to measure the transfer rates and the reason for taking into account the angular dimension only is related to the sphere volume which is considered small as a surface for cooling area.

It is seen from the related figures of local Nusselt number vs. angle measured from FSP of sphere that values of Nusselt numbers decreases from run1 (higher velocity of air) to run 4 (the lower one) and decreases also with increasing θ until it reaches a minimum value when $\theta = \boldsymbol{\pi}$, after that an increase in local heat transfer coefficient is notified and will progress until $\theta = 2\boldsymbol{\pi}$ from which one complete revolution is obtained and maximum values of local measurements are recorded for each run.

Conclusions

From calculations of present work it is concluded that for the values of Reynolds number less than 2×10^5 the Nusselt number agree well with Kendoush correlation (1995) especially for front region and separation angle from the boundary layer is held constant approximately at 87^{0} from FSP of sphere for Reynolds number between (12894 – 33282) and the maximum local heat transfer coefficient lies at the FSP ($\theta = 0$) and the minimum value at the RSP ($\theta = \boldsymbol{\pi}$).

The local and average heat transfer coefficients are based on the assumption of constant wall temperature of sphere approximately. As a suggestion for the future work it is possible to investigate the heat transfer parameters for condition of constant heat flux.

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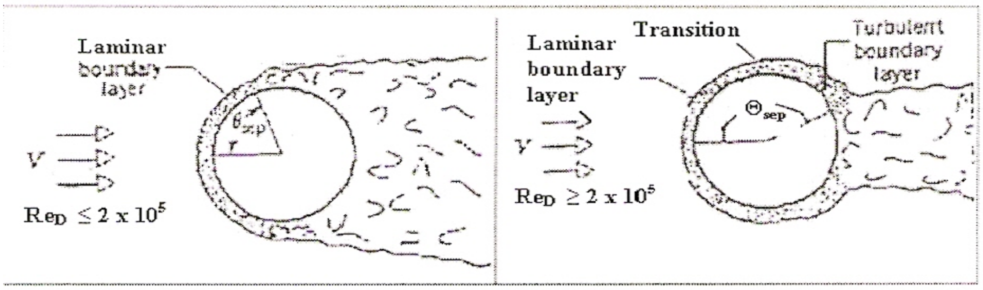

Figure (1) The Effect of Turbulence on Separation Around a Sphere
[Incropera 1996]

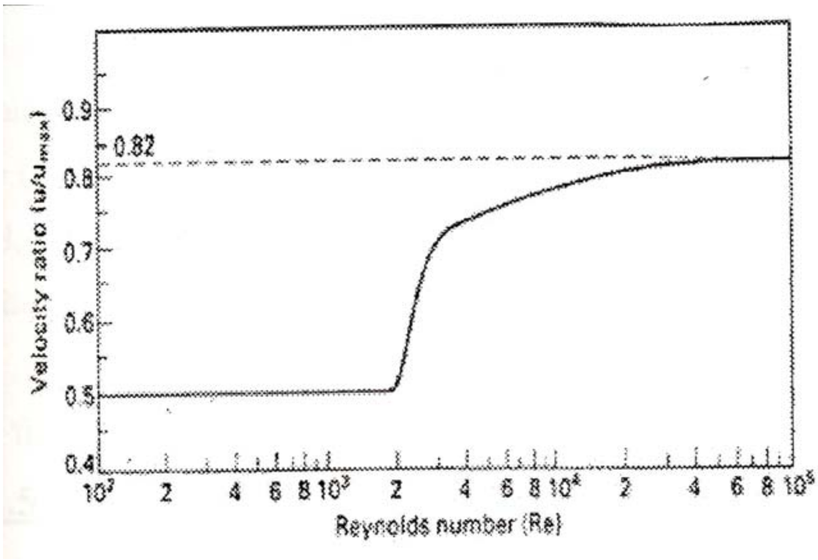

Figure (2) Variation of U/U $_{max}$ with Reynolds Number in a Pipe
[Richarson 1996]

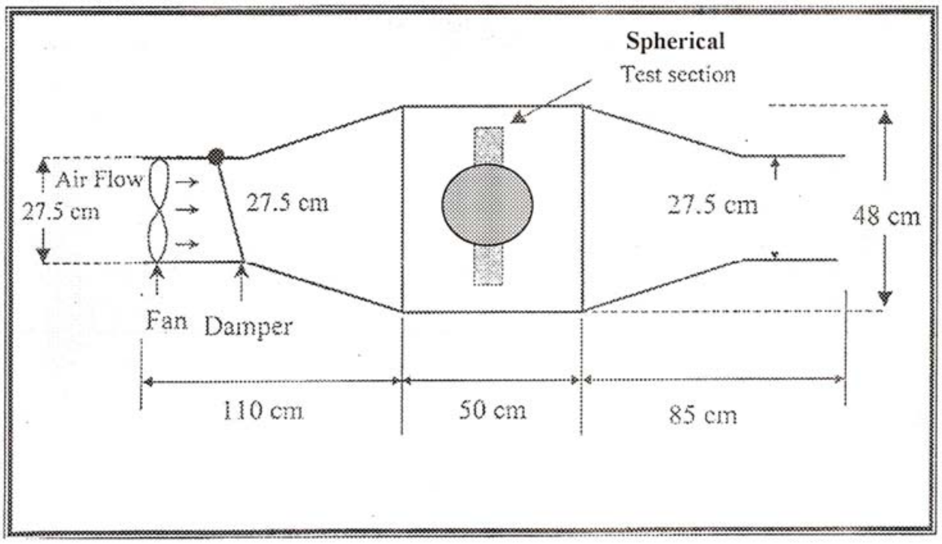

Figure (3) Schematic Diagram Shows the Experimental Channel

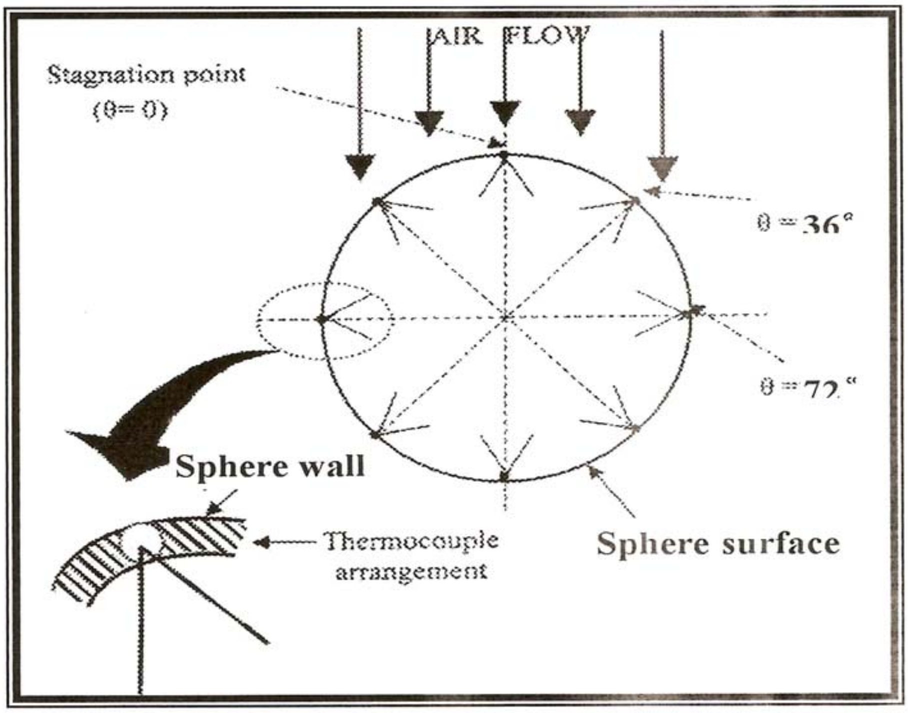

Figure (4) Arrangement of Thermocouples in The Sphere

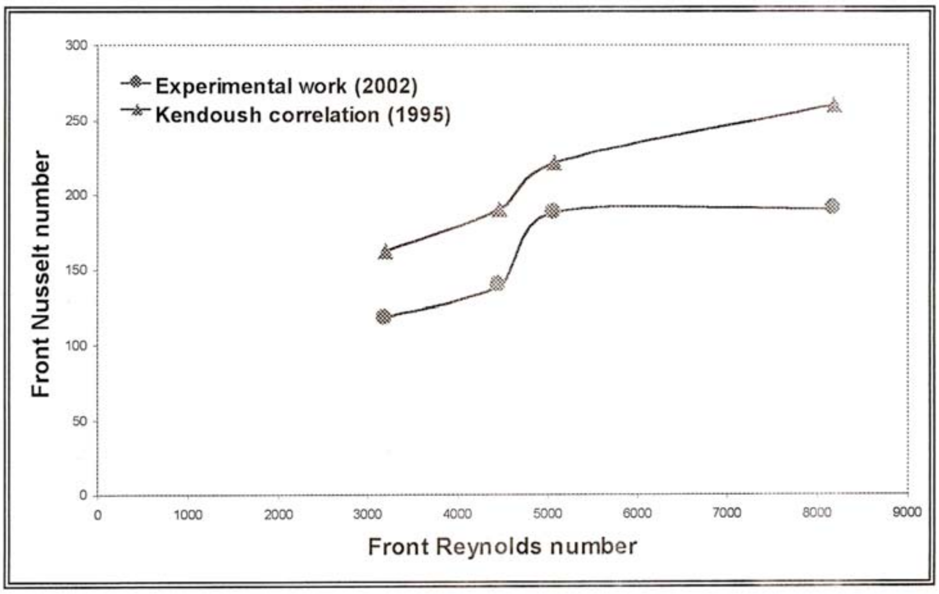

Figure (5) Relation Between Front Nusselt and Reynolds Numbers for Sphere Heated by Water at Temperature 70 ^{o}C

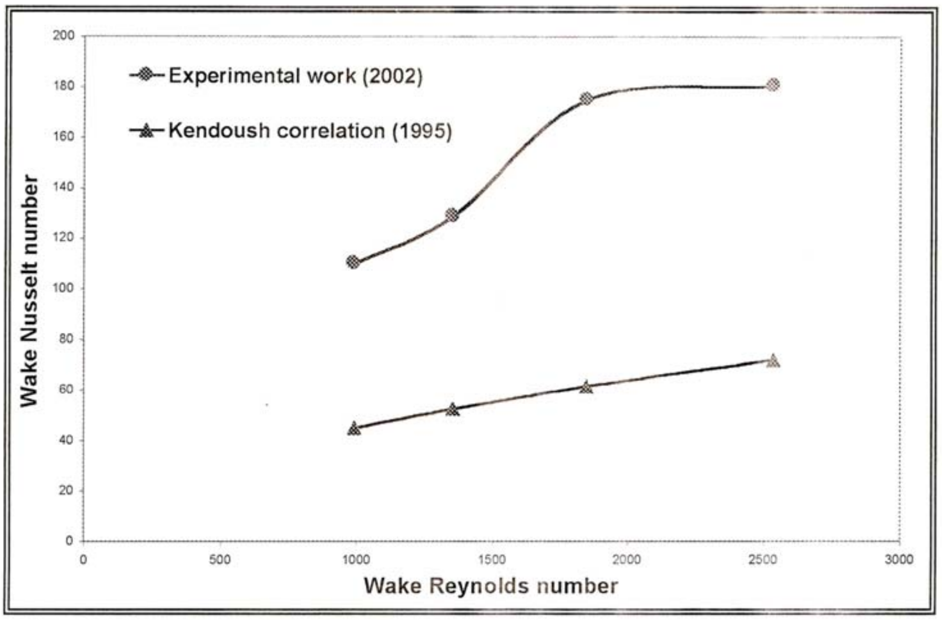

Figure (6) Relation Between Wake Nusselt and Reynolds Numbers for Sphere Heated by Water at Temperature 70 ^{O}C

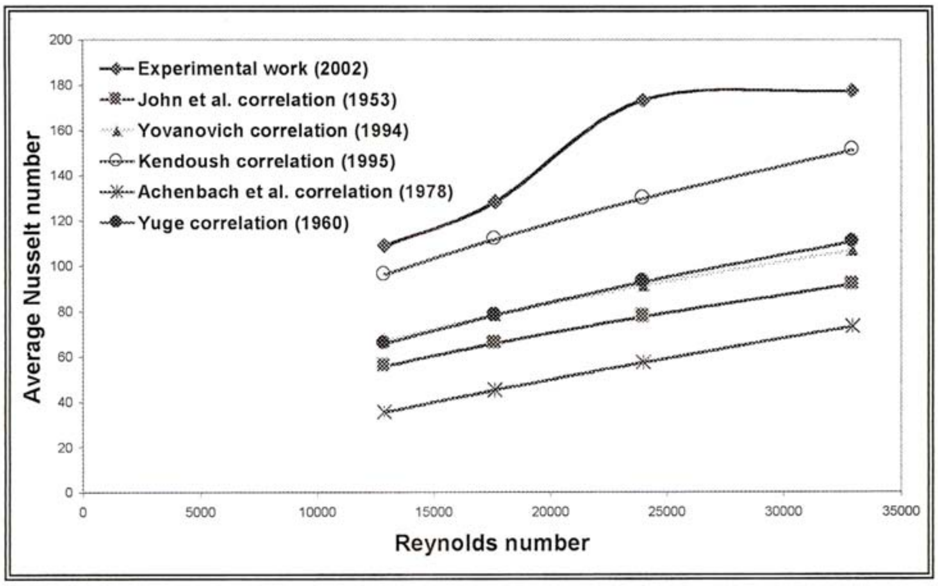

Figure (7) Relation Between Average Nusselt and Reynolds Numbers for Sphere Heated by Water at Temperature 70 ^{O}C

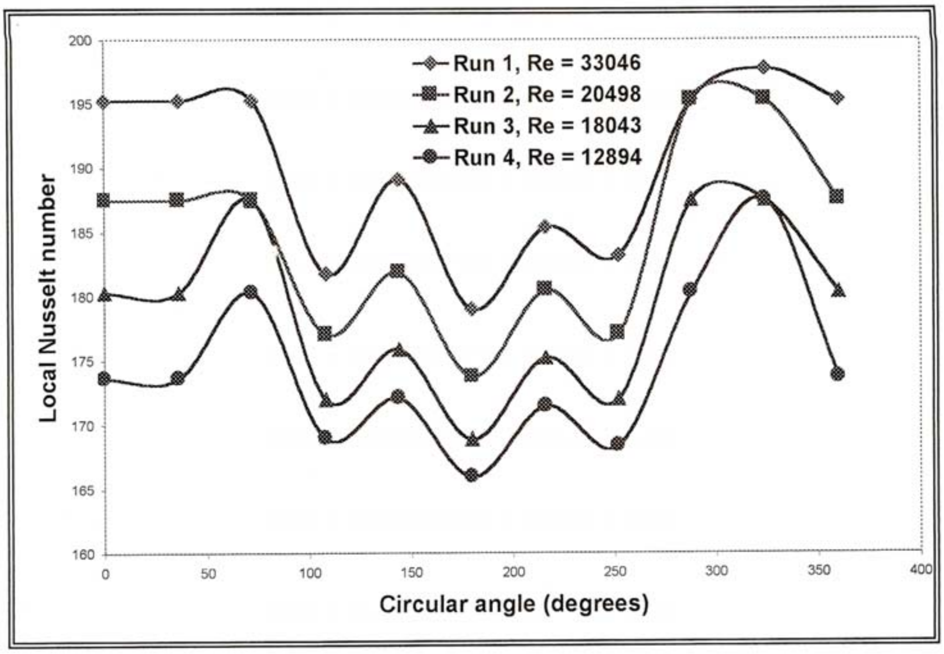

Figure (8) Relation Between Local Nusselt and Circular Angle for Sphere Heated by Water at Temperature 60 ^{O}C