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Experimental investigation in charge superposition principle determination of free convection heat transfer coefficient in aqueous solution containing different concentration of salt around a cylinder with constant heat flux

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ABSTRACT

The aim of his research is design of laboratory instrument. So, this investigation provides guidelines for the laboratory tests to measure the free heat transfer coefficient of a cylinder which is released to the environment of different electrolyte solutions with different concentrations. First, a special laboratory device designed and calibrated to be made. The used electrolyte solution samples of sodium chloride are with different concentrations of 10, 20, 40, 60, 80 and 100% as mass percent. Second, experimental curves are drawn in each case which show Nusselt numbers according to Rayleigh number. The obtained results are compared with experimental results obtained by Sir Winston Churchill – Cho. The results show a very good approximation. Finally, a new correlation for predicting the free convective heat transfer coefficient around the cylinder in electrolyte solutions will be suggested.

KEYWORDS

Heat transfer coefficient;
Electrolyte solutions;
Nusselt numbers;
Winston Churchill–Cho number;
Sodium chloride.

INTRODUCTION

Free convective heat transfer from cylindrical surfaces has been studied numerously during the past 45 years.

Königsberger et al. in 2008 studied on the density of salt solutions of magnesium chloride and nickel chloride. They showed the density and viscosity increases linearly with increasing concentration and also viscosity increases from 25 °C to 90 °C. Also, they stated heat capacity of the solutions is significantly reduced with increasing concentration.

Akhtar et al. in 2011 conducted research on some of the electrolyte solution. They showed the thermal properties of the solution significantly increased by adding nanoparticles. Wang et al. in 2011 studied on some of the electrolyte solution containing alkali ions. They stated increasing the alkali ions, increased thermal properties and also crystal structure of solution improved.

Zhang et al. in 2011 conducted a study on electrolyte complexes. They stated the ion concentration in the solutions affected their specifications significantly so, that some of them used as a catalyst. Maldonado et al in 2012 studied on the conductive heat transfer coefficient and diffusion coefficient of the electrolyte solution. They expressed the vapor phase of the liquid phase is effective on temperature and other thermal properties of the solution.

Part of the process including design, construction and calibration of a laboratory instrument with laboratory measurements of free convective heat transfer coefficient of a cylindrical shape to non-electrolyte solutions with different concentrations of the medium is proposed in this research. The specific purpose of this study is providing guidelines for the laboratory tests. The most important issue is the method of temperature measurement in these experiments.

In initial design, cylindrical surface temperature is measured by thermocouples which are located on the cylindrical surface but the results are unrealistic. So some location modification is proposed to reach acceptable results that will be described comprehensively in the following sections. Finally, recommendations are presented in order to get better results.

METHODOLOGY

Experimental apparatus

Points in terms of mechanical and thermal design of the device are as follows:

1. Possible heat flux must be distributed evenly to the entire surface of the cylindrical element by element to minimize thermal gradient along the axis.
2. Heating elements shall be insulated at both sides and heat loss from the sides may be reduced to a minimum.
3. Supports with a low coefficient of thermal conductivity should be selected to have less heat loss. Here the base glass is used.
4. In thermal sensors selection, installation and temperature range which measure have to be accurately enough.
5. Machine installation and handling cost may be convenient.

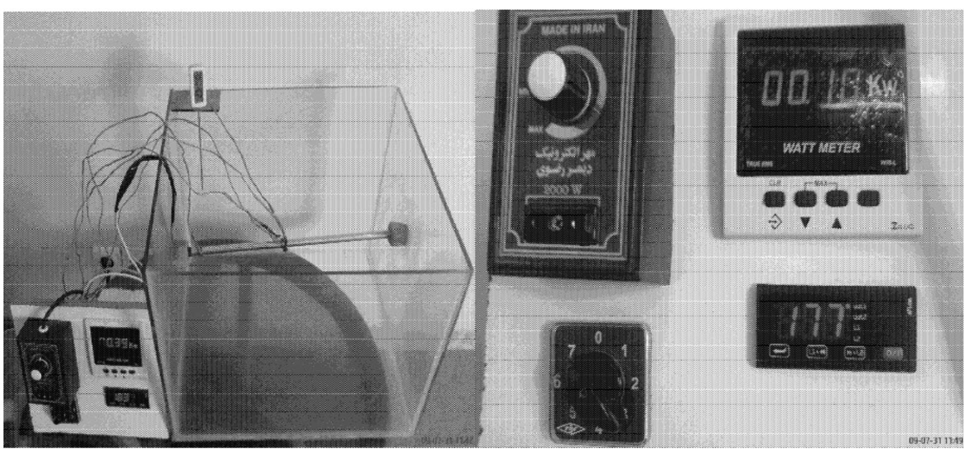

Figure 1 : The proposed apparatus which is used in these experiments

Heating element

A stainless steel cylinder with a diameter of 12.7 mm and a length of 40 cm is used to create a constant heat flux boundary condition and an electrical resistor placed in line with the axis of the cylinder. The around of the cylinder is filled with completely smooth and homogeneous stone powder to avoid contact with electrical resistance and the cylindrical body as well as uniform distribution of heat flux.

Meanwhile, in order to reduce thermal energy loss at the two ends of elements in contact with the walls of the aquarium (pool test), the element is completely insulated at the junction of the wall and the glass pool by 2 cm glass wool which has low thermal conductivity coefficient of about $0.038\,W/m.K$. Figure 2 is a picture of the thermal element.

As is shown, the resistance in the 367-355 range varies due to temperature. Thermocouple type J is used in temperature measuring of the cylindrical tube surface considering range of temperature variations and accu-

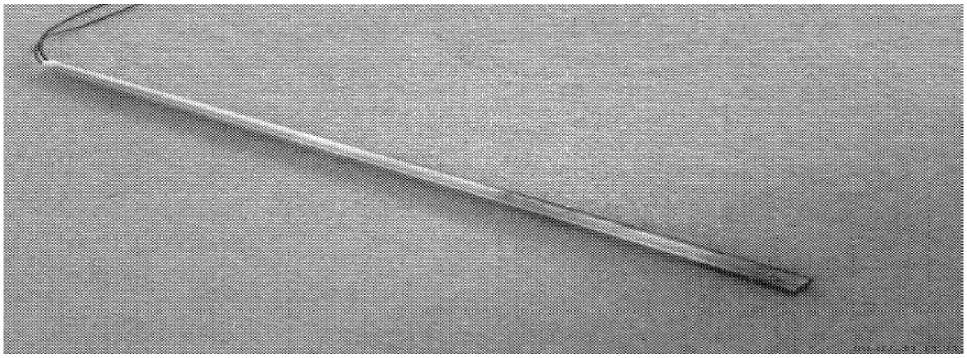

Figure 2 : View of the thermal element

TABLE 1 : Electrical resistivity profile

amplitude (Ω) Resistance	(V) Input voltage	Resistor material
394–406	0–230	Ni-Cr alloy

racy required. Then four Thermocouples are closed by a clip in the middle section of the tube in equal distances from each other.

The middle section of the tube is selected because the temperature gradient along the tube is zero by taking inconsiderable partial loss of thermal energy at both ends of the insulation. A thermocouple is mounted at the junction of the distal end of the tube with the pool wall (insulated part). The thermocouple measures (Tb) which is used in the calculation of thermal energy loss (QL).

Duration of test

Finding empirical steady state relations in experiments; so specified time should be spent in each of the thermal energy and the surface temperature should be constant. The time will depend on the type of fluid, the volume of fluid and the thermal element dimensions. The average time required to reach steady-state in the experiments (constant surface temperature) at different values of thermal energy was about 80 min.

Outlines of test

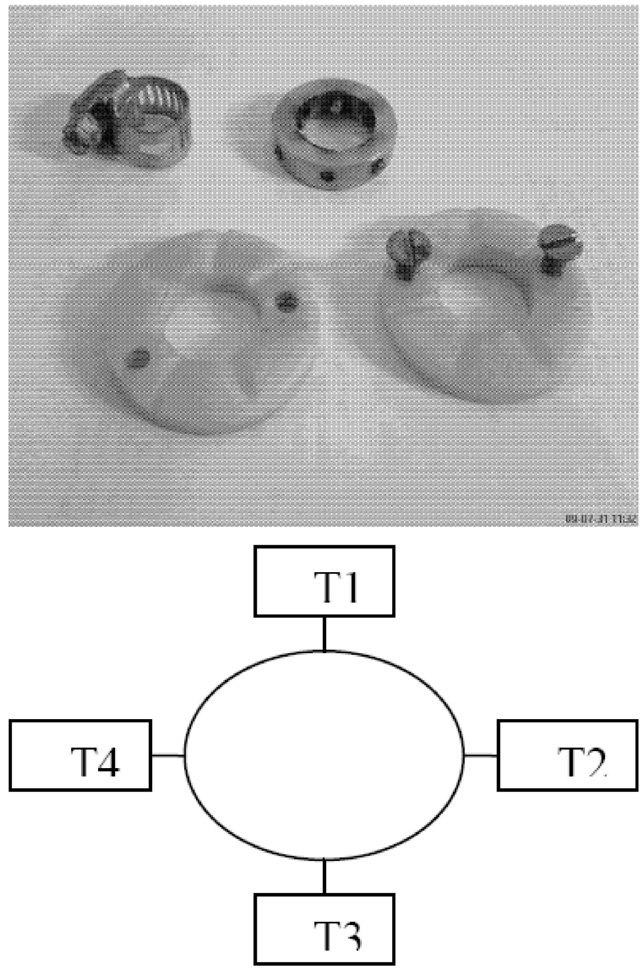

Figure 3 : The used clip in the experiment and the schematic of thermocouples locations

1. The experimental apparatus is mounted in suitable place to minimize the amount of air flow in different directions.
2. Heating element is connected to a variable voltage source (Dimmer), a voltage meter has been installed between the elements and the Dimmer to read different amounts of thermal energy (QT). The test is started with 60 watts of heat energy and repeated with 60, 80, 95, 110 and 125 W with changes in the amount of dimmer. It is obvious that the specific time about an hour is needed in any case to steady-state conditions (constant surface temperature) are reached.
3. The temperatures and the value of thermal energy (QT) are written down at steady-state conditions.
4. Due to the exchanged radiation thermal energy, mea-

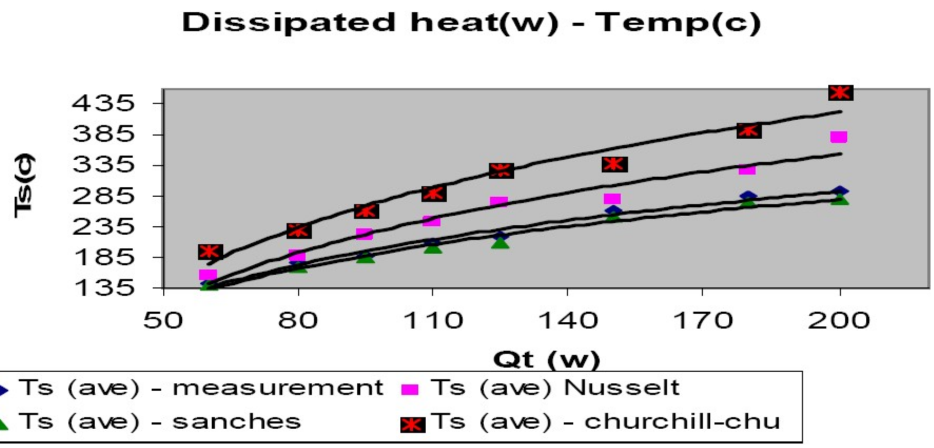

Figure 4 : Experimental temperatures were compared with experimental results obtained by Sanchez and the results of Nusselt relations of trial and error obtained by Cho - Churchill for free convective heat transfer in the air.

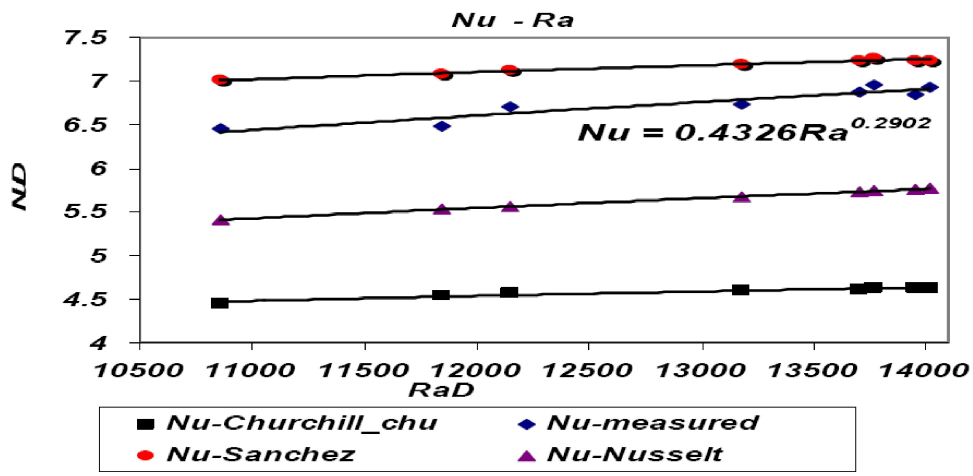

Figure 5 : Comparison of experimental Nusselt with results obtained by the experimental nusselt relations, Sanchez and Cho-Churchill for free convective heat transfer in the air.

suring temperature in remote areas of the testing machine and the temperature of the pool walls (Chamber walls) is necessary. But the temperature of the fluid adjacent to the pool wall is just measured due to the volume of fluid and the small temperature difference between the wall of the pool and room.

5. Data is recorded and analyzed by the basic equations of heat transfer in order to reach the proper relation.

Calibration and introduction of free convective heat transfer equation for a cylinder with constant heat flux in air

Some experiments for free convective heat transfer are held in order to calibrate the instrument after design and manufacturing of the device. The obtained experimental results in air compared with experimental observations made by Mr. Churchill - Cho and Mr. Nusselt which carried out for a cylinder with an infinite ratio of length to diameter (L/D=™(. Also, the results are compared with obtained results by Mr. Sanchez, who also experimented with the limited ratio of cylinder length to diameter and under the close experimental conditions with the used conditions in this work.

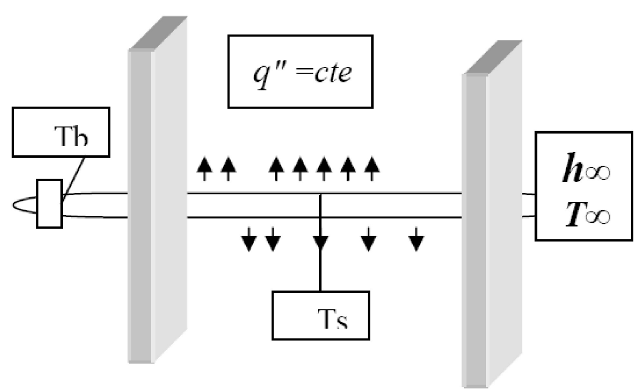

Figure 6 : The proposed experimental instrument

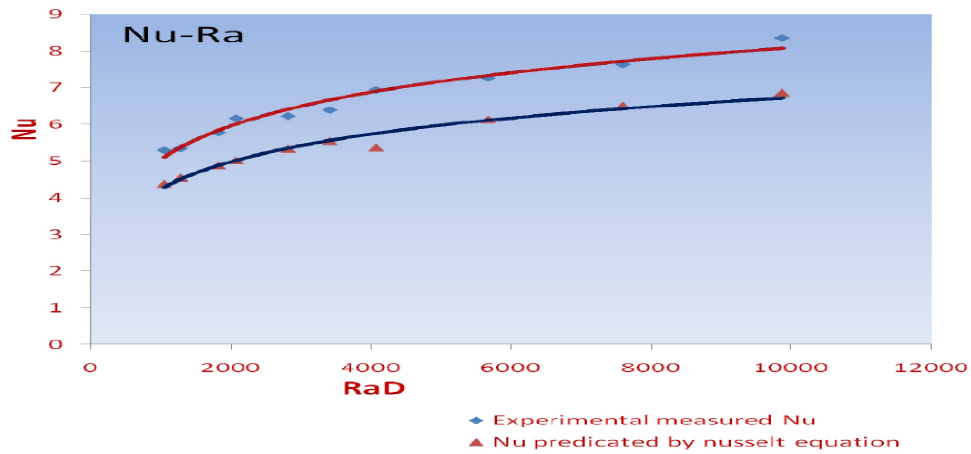

Figure 7 : Comparison of experimental Nusselt obtained by testing the device with the Nusselt values obtained by Nusselt correlation for free convection heat transfer in water

TABLE 2 : Thermal energy loss in different heat fluxes, free convection heat transfer in % 20 NaCL solution

QT watt	Qloss radiation	Qloss conduction	Qloss Total	QFree convection
65	1.8	3.35	5.15	59.85
85	2.42	4.76	7.18	77.82
110	2.8	5.01	7.81	102.19
125	3.16	5.5	8.66	116.34
175	4.47	7	11.47	163.53
210	5.17	8.5	13.67	196.33
240	5.53	9	14.53	225.47
280	6.5	10.01	16.51	263.49
320	7.414	10.612	18.026	301.974
400	9.159	11.124	20.283	379.717

Then comparison tables and calculations are presented in detail. TABLE 2 presents the temperature values measured at different values of power and environment temperature.

In this part, obtained temperatures are compared with the experimental values obtained with Nusselt correlations, Cho - Churchill and Sanchez. So, thermal energy loss by radiation from the surface of the cylindrical elements as well as the convective heat loss of both ends must be calculated and then after deduction from the total power, actual amount of convective heat transfer achieved. Using relations and trial and error method calculations get the temperature. The results of these calculations are shown in Figure 4.

Since most experimental Nusselt are as power functions of the dimensionless Rayleigh numbers $\overline{Nu} = CRa^{n}$. Here the Nusselt numbers is fitted of the power function by the method of least squares. This function is presented for free heat transfer between air and cylinder with constant flux of heat:

$$\overline{Nu} = 0.4326Ra^{0.2902} \quad (1)$$

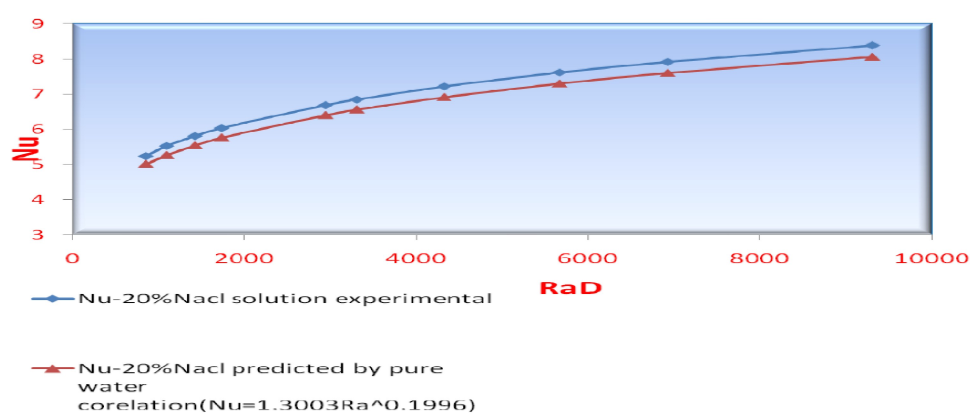

Figure 8 : Comparison of experimental Nusselt for % 20 NaCl water solution obtained by proposed instrument with Nusselt values obtained by fitting equation for free heat transfer $\overline{Nu} = 1.3003\ Ra^{0.1996}$.

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EXPERIMENTS

Five different concentrations of sodium chloride electrolyte solution at 0, 20, 40, 60, 80 and 100 percent of mass are used in this study. The results of each case are presented in detail in the form of tables and graphs.

Nu-Ra ¬ chart shows that experimental values are about 4.13 percent higher than Nu-Ra curve obtained from the correlation curve and is shifted upward in solution with 20% of the NaCl concentration.

Nu-Ra ¬ chart shows that experimental values are about 5.29 percent higher than Nu-Ra curve obtained from the correlation curve $\overline{\mathbf{Nu}} = 1.3003\ \mathbf{Ra}^{0.1996}$ and is shifted upward in solution with 40% of the NaCl concentration.

Nu-Ra ¬ chart shows that experimental values are about 10.2 percent higher than Nu-Ra curve obtained from the correlation curve $\overline{\mathbf{Nu}} = 1.3003\ \mathbf{Ra}^{0.1996}$ and is shifted upward in solution with 60% of the NaCl concentration.

TABLE 3 : Thermal energy loss in different heat fluxes, free convection heat transfer in % 40 NaCL solution

QT watt	Qloss radiation	Qloss conduction	Qloss total	QFree convection
65	2	3/9	5/9	59/1
85	2/5	4/5	7	78
110	3/845	5/321	9/166	100/834
125	4	6/01	10/01	114/99
175	5/22	7/801	13/021	161/98
210	5/921	8/820	14/741	195/26
240	7/004	10/011	17/015	222/985
280	7/516	10/7	18/216	261/784
320	8/212	11/5	19/717	300/288
375	10/62	14/001	24/621	350/379

TABLE 4 : Thermal energy loss in different heat fluxes, free convection heat transfer in % 60 NaCL solution

QT watt	Qloss radiation	Qloss conduction	Qloss Total	QFree convection
65	2/451	4/512	6/693	58/037
85	3/14	6/012	9/152	75/848
110	3/94	6/8	10/74	99/26
125	4/532	7/7	12/232	112/768
175	6/869	8/8	15/669	159/331
210	7/08	11/01	18/09	191/61
240	7/848	12/51	20/358	219/642
280	8/514	13/302	21/816	258/184
320	10/107	14/51	24/617	295/383
350	12/01	15/523	27/533	347/467

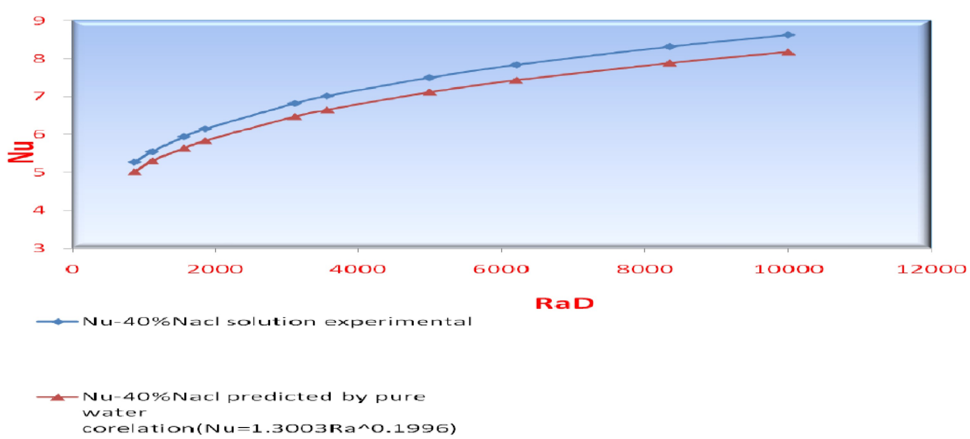

Figure 9 : Comparison of experimental Nusselt for % 40 NaCl water solution obtained by proposed instrument with Nusselt values obtained by fitting equation for free heat transfer $\overline{\mathbf{Nu}} = 1.3003\ \mathbf{Ra}^{0.1996}$.

Nu-Ra ¬ chart shows that experimental values are about 16.51 percent higher than Nu-Ra curve obtained from the correlation curve and is shifted upward in solution with 80% of the NaCl concentration.

Nu-Ra ¬ chart shows that experimental values are about 20.6 percent higher than Nu-Ra curve obtained from the correlation curve and is shifted upward in solution with 100% of the NaCl concentration.

RESULTS AND DISCUSSIONS

To compare the effect of different concentration of

TABLE 5 : Thermal energy loss in different heat fluxes, free convection heat transfer in % 80 NaCL solution

QT watt	Qloss radiation	Qloss conduction	Qloss Total	QFree convection
65	3/184	5/110	8/294	56/706
85	3/919	6/87	10/789	74/21
110	5/011	7/521	12/532	97/468
125	5/9	9/11	15/01	109/99
140	6/94	10/79	17/73	122/268
160	7/83	12/29	20/12	139/88
175	8/41	12/82	21/23	153/77
190	8/707	14/01	22/717	167/283
210	9/62	15/52	25/14	184/86
240	12/529	17/2	29/729	210/271

TABLE 6 : Thermal energy loss in different heat fluxes, free convection heat transfer in % 100 NaCL solution

QT watt	Qloss radiation	Qloss conduction	Qloss total	QFree convection
65	4.215	5.81	10.025	54.975
85	5.212	7.87	13.082	71.92
110	6.112	8.423	14.535	95.465
125	7.038	10.64	17.678	107.322
140	8.01	12.08	20.09	119.91
160	8.96	14.5	23.46	136.54
175	9.781	15.28	25.06	149.94
190	10.03	16.34	26.37	163.63
210	11.1	17.84	28.94	181.06
240	15.01	19.4	34.41	205.59

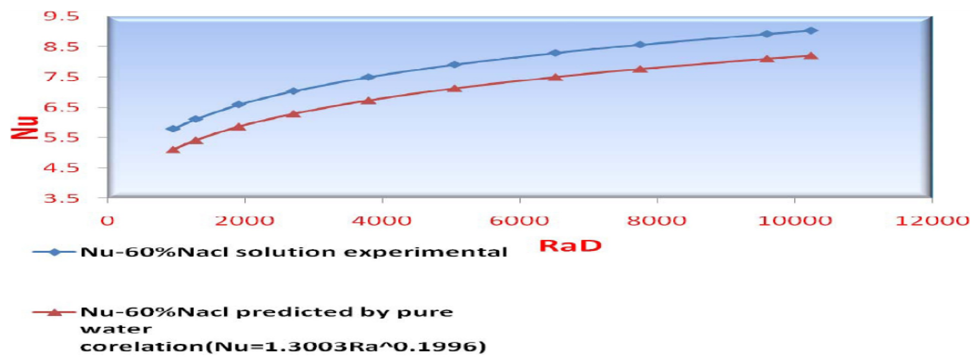

Figure 10 : Comparison of experimental Nusselt for % 60 NaCl water solution obtained by proposed instrument with Nusselt values obtained by fitting equation for free heat transfer $\overline{Nu} = 1.3003\, Ra^{0.1996}$.

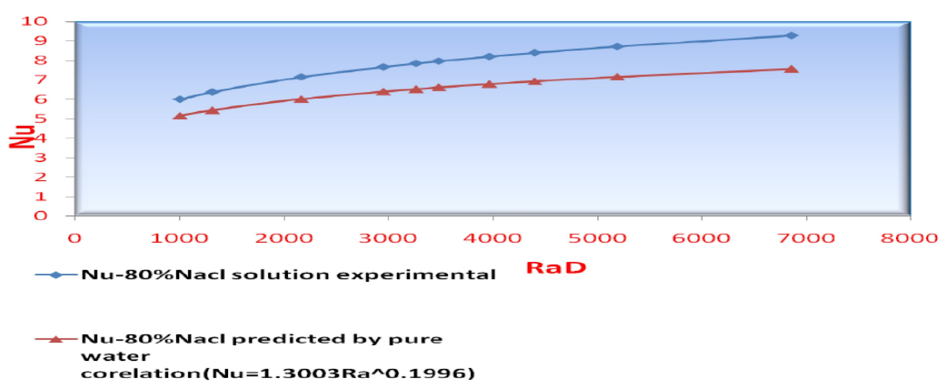

Figure 11 : Comparison of experimental Nusselt for % 80 NaCl water solution obtained by proposed instrument with Nusselt values obtained by fitting equation for free heat transfer $\overline{Nu} = 1.3003\, Ra^{0.1996}$

sodium chloride in the resulting equations, the related Nusselt numbers are obtained using different assumed Rayleigh numbers in different solutions and general results are presented in the following tables and figures.

As mentioned in the Table and in the figure, increase the concentration of sodium chloride solution in water makes values in the Nu-Ra curve higher than the Nu-Ra curve of pure water. So Nusselt values in terms of Rayligh numbers in the curve for 20% sodium chloride solution are shifted approximately 13.4% upward compared to the Nusselt values for pure water.

Similarly, for 40% sodium chloride it is about 5.29%

, for 60% sodium chloride solution it is approximately 10.2%, in 80% sodium chloride solution it is about 16.51% and for 100% sodium chloride solution it increases about 20.6%.

TABLE 7 : Correction factor used in the proposed relation for different concentrations of electrolyte solutions

Electrolyte concentration (Wt%)	C
%20	1.0462
%40	1.0540
%60	1.1177
%80	1.1949
%100	1.2553

Experiments indicate that the increase of the concentration of sodium chloride in water, make higher values of Nusselt number versus Rayleigh number. So, the curve of 100% Sodium Chloride solution is above the other curves, respectively 80%, 60%, 40% and 20% of NaCl concentration are at the lower positions.

In other words, the increasing trend will continue to 100% sodium chloride concentration in water and this is clearly shown in the Figure 13.

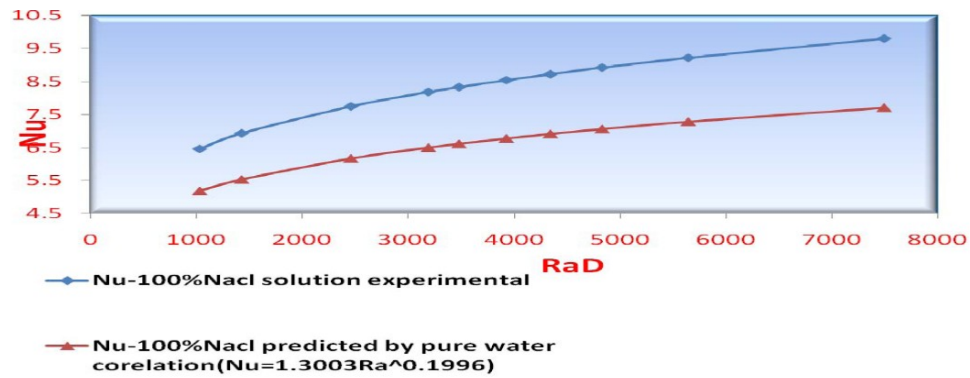

Figure 12 : Comparison of experimental Nusselt for % 100 NaCl water solution obtained by proposed instrument with Nusselt values obtained by fitting equation for free heat transfer $\overline{\mathbf{Nu}} = 1.3003\ \mathbf{Ra}^{0.1996}$

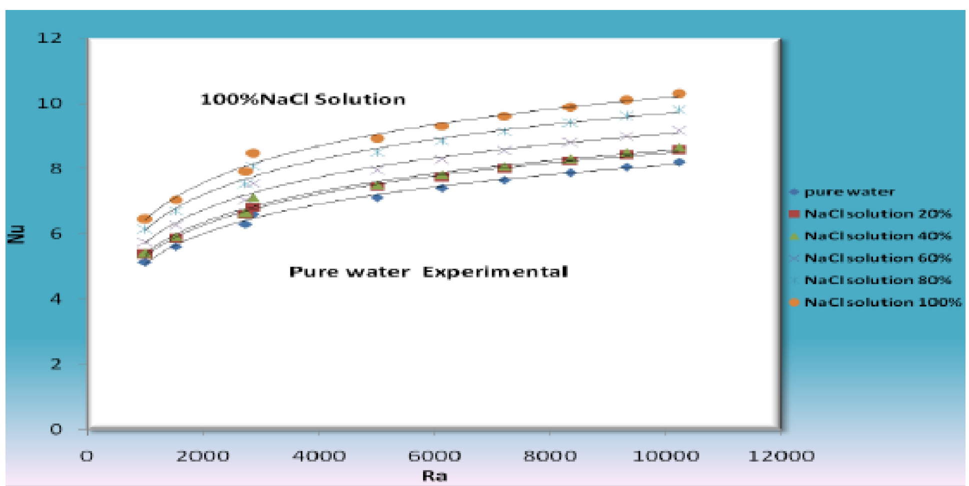

Figure 13 : Nusselt numbers compared to the fitted equations to solutions of different concentrations of sodium chloride in the given rang

CONCLUSION

Nusselt number versus Rayleigh number curve behavior changes with different concentrations of sodium chloride in water, comparing with the curve for pure water it is linked to the interactions between the molecular of electrolyte solutions, theoretically. The obtained experimental results can be considered and can be further tested for other fluids and electrolytes, in theory. Finally, a relation for Nusselt number in different concentrations of electrolyte solutions is proposed and a correction factor in relation of the pure water is presented.

$$\overline{Nu} = C \times 1.3003 Ra^{0.1996} \quad (2)$$

The constant coefficient,, for electrolyte solutions at different mass concentrations, are as follows:

It is obvious that the constant coefficient, C, for different concentrations of electrolyte solutions can be achieved through interpolation between the values obtained.

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