Heat Transfer Enhancement in vertical Mounted Tube Subjected to Uniform Heat Flux by using Electrolysis Bubble

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ABSTRACT

In the present work, experimental and numerical investigations had been carried out to investigate the effect of sub-millimeter bubbles injection on heat transfer coefficient of upward flowing water in vertical mounted tube subjected to uniform heat flux. The experimental apparatus consists of a test rig designed and built to conduct the experiments. A circular tube, test section was designed and constructed from the copper and heated by an electrical heater on its outer surface. The dimensions of copper pipe was (length= 0.7m, diameter= 0.05 m, thickness= 1.5 mm). Water temperature at inlet was kept constant at (32°C). Thermocouples distributed longitudinally at different radial distances between cylinder surface and its center at seven sections, in addition to the fluid inlet and outlet were used to measure temperatures. Bubbles generation was performed in test section by using a proper ionization current that will be passed across the anode and cathode electrodes to produce hydrogen bubbles and oxygen bubbles at different intensities. The experiments were conducted using heat fluxes (13641 and 22736) W/m^2, water mass flow of (2, 3 and 4) lit/min, mass flow rate of hydrogen and oxygen bubbles were (0.02 , 0.025) lit/min respectively and Reynolds number (1214, 1783 and 2300) for water. The results showed that an enhancement of 25.5% was obtained in the averaged Nusselt number with using ionization bubbles compared with the case without bubbles.

Keywords

Hydrogen and oxygen bubbles, Bubble injection, Two-phase flow, Water electrolysis

1. INTRODUCTION

Micro-bubble injection is commonly achieved by injecting a cloud of micro-bubbles into the boundary layer by either bubble generation via electrolysis or direct injection through slots or porous skins. This method has great potential for heat transfer enhancement or drag reduction. Heat transfer under the effect of bubbles was investigated through many researches. Baliffo, et al.,[1] investigated experimentally the heat transfer characteristics of cylinder in cross flow. Effect of bubbles by electrolysis water and nucleate boiling was investigated. The following conditions with (0.1M) sodium hydroxide aqueous solution was used. The test rig consisted of pump, control valve, test section and tank of water .Test section of (5 cm) long and (1.2 mm) hollow cylinder arranged in cross flow. The test section worked as electrode to generate hydrogen bubbles. The experiments covered heat flux within the range of (0- 600W/m^2), fluid velocity of (6.4 -10m/s), current density of (0 – 2 x10^3 A/m^2), temperature difference (0 -7ºK). The results showed that wall temperature kept below the saturation temperature and that heat transfer coefficient was increased versus temperature difference. Hassan et al.,[2] investigated experimentally sub-millimeter-bubble injection on two dimensions and turbulent flow in horizontal rectangular cast acrylic channel. Water electrolysis was used to generate micro bubbles. The particle tracking velocimetry was used to measure velocity. The Reynolds number of the main flow was (5128), bubble diameter was (30 µm) and void fraction was within the range of (2.4% to 4.9%) were used in the experiments. The effect of the micro-bubble injection near the wall caused decrease in the Reynolds shear stress when the value of local void fraction was increased. Lu et al., [3] investigated experimentally the effect of small hydrogen micro bubbles on drag reduction in circulating water in to horizontal channel. The drag reduction was measured by shear transducers located downstream from the electrode center. Micro bubbles were produced by electrolysis of water. Experiments were carried out with mean velocities of (1, 1.5 and 2 m/s), micro-bubbles diameters (10 to 60µm), void fraction (0% to 0.04%) and current values of (0.5 and 1.0A). The experimental results compared with air bubbles and showed that the bubbles form electrolysis was more effective for drag reduction than air bubbles and both bubbles were very different from each other. It was concluded also that the mechanism of drag reduction was more effective versus bubble diameter and void fraction. Kitagawa, et al., [4] investigated experimentally the effect of sub-millimeter-bubble injection on two-dimensional laminar flow along vertical plate in rectangular channel. Experiments were carried out using water electrolysis to generate micro bubbles. Particle tracking velocimetry technique and thermocouples were used to measure temperature and velocity respectively. The values of heat fluxes were (533, 947 and 1.480 W/ m^2) and bubbles rate values were (34, 45 and 57mm^3/s). The results showed that the enhancement of heat transfer ratio increased from (1.35 to 1.85). It was noticed also that this ratio increased by increasing bubble flow rate or decreasing heat flux range.

Kitagawa, et al. [5] carried out experimental and numerical studies heat transfer enhancement by injection sub millimeter bubbles in to rectangular channel for laminar natural convection along vertical plate. Experiment were conducted at range of heat fluxes (533, 947 and 1480 W/m^2) and bubbles flow rates (33, 45 and 56mm^3/s). Water electrolysis was used to generate micro-bubbles. Temperature and velocity measured by using thermocouples and particle tracking velocimetry technique. Bubble injection effect, bubble sizes and heat transfer enhancement had been carried out in order to clarify the numerical results. It's concluded that, the coefficient of heat transfer ratio enhancement increased from

(1.3 to 2.2). It was noticed also, that the constant rate of bubble injection caused an increase in heat transfer coefficient as the bubble diameter decreased. Kitagawa, et al. [6] studied experimentally the effects of sub-millimeter bubbles injection in laminar mixed-convection flow in a vertical channel. Water electrolysis was used to generate micro bubbles. Temperature and velocity measured by using thermocouples and particle tracking velocimetry technique. Reynolds number range (100, 125 and 150), bubble flow rate (40 mm^3/s) and heat flux of (1480 W/m^2) were used. It's concluded that, enhancement coefficient of heat transfer ratio decreased with increasing Reynolds number. Kitagawa, et al. [7] studied experimentally effect of micro bubbles on laminar mixed-convection flow in a vertical channel. Experiments were conducted with Reynolds numbers (100, 150 and 200), bubbles flow rates (33, 34 and 35mm^3/s) and range of hear flux ($1.79x10^3 W/m^2$). Water electrolysis was used to generate micro bubbles. Temperature and velocity measured by using thermocouples and particle tracking velocimetry technique. The results showed that, the presence of bubbles caused an enhancement in the mixing and high heat transfer rates from (1.24 to 1.38) compared with single phase flow. Kitagawa et al. [8] studied experimentally the effect of sub-millimeter-bubble injection on turbulent flow along vertical plate in channel. Electrolysis of water was used to generate micro bubbles. Experiment were conducted with heat flux rates (533, 947 and 1480W/m^2) and bubble flow rates (33, 56 mm^3/s). Temperature and velocity measured by using thermocouples and particle tracking velocimetry technique. It's concluded that, the ratio of heat transfer coefficient enhancement was from (1 to 1.9) in the transition region. Also, bubble flow was increased to (56 mm^3/s) in the turbulent region and more enhancement was obtained for heat transfer coefficient ratio. Kitagawa, et al., [9] studied experimentally the effect of bubbles injection on natural convection flow along a vertical plate in channel. This study focused on flow transition phenomena to turbulence flow by method of bubbles injection. Experiments were conducted with bubbles flow rate of (56mm^3/s) and hear flux ranges of (530, 950 and 1480 W/m^2). Water electrolysis was used to generate micro bubbles. Positions of bubble injection were at (1.6 and 3.6mm) distance from the heated wall. Tracking velocimetry technique and thermocouples are used to measure temperature and velocity, respectively. The results showed that the transition to turbulence delayed at position injection (1.6 mm) and accelerated at (3.6 m) which was effected by the liquid velocity fluctuation on the laminar boundary layer due to the different between (1.6 and 3.6 mm). Hara et al., [10]investigated experimentally the effect of micro bubbles generating by water electrolysis on friction drag reduction for turbulent flow in vertical channel . The Reynolds number of (4800), diameter of micro-bubble (30–200) μm ,velocity of water 1m/s ,inlet water temperature (15°C) ,dimension of electrodes (45x 5x 5) mm, and current values (0.02, 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2) Amp were used in the experiments. Particle tracking velocimetry used to measure velocity fields. The results suggested that the drag of friction reduction was (30%) compared to single phase at low void fractions ($\alpha \approx 3x10^{-4}$), effective drag reduction was at distance downstream from array of electrode. High speed video camera used to visualize flow patterns. Kitagawa and Murai [11] studied experimentally effect of micro bubble injection on natural convection heat transfer for flow along heated plate. Experiments were conducted with bubbles flow rates of (30 and 42 mm^3/s) and heat flux range of (14800 W/m^2). Water electrolysis was used to generate micro bubbles. Image processing technique was used to measure diameter of bubble, velocity of bubble and thickness of bubble layer .Thermocouples were used to measure temperatures. The results showed that the coefficient of heat transfer ratio enhancement from (1.6 –2.0) and (1.5–2.0) in laminar and transition regions respectively. Kitagawa et al. [12] investigated experimentally the effect of micro bubbles and small particles injection with different specific gravities on the two phase flow. Particle image velocimetry technique was used to measure gas-phase velocity. Micro bubbles were injected at the bottom while small particles were injected on the top of the channel. It was concluded from the results that mean kinetic energy of the two phase flow with small particles was significantly lower than flow with micro bubbles only. In addition, specific gravity of the small particles had significant effect on the mean kinetic energy of the two-phase flow. Kitagawa and Murai [13] studied experimentally effects of micro bubble injection on vertical wall. This study clarified the characteristics of micro bubble motion and constant bubble flow rate. The measurement positions in these experiments were (x= 250, 500, 750 mm) along non heated flat plate and bubble flow rate (42mm^3/sec). Particle tracking velocimetry for velocity measurements was used. In these experiments, the results showed that bubble numbers density increased close to the wall and there was a pulsated rise of the micro bubble swarm by wave generation and bursting motion of the micro bubble amplification of the waves. Kitagawa et al. [14] investigated experimentally the effect of micro bubbles generating by water electrolysis along a vertical plate in channel. An effect of inclination angle of plate was studied in the experiment. The measurement positions in these experiments were equal to (70, 170, 270 and 370) mm along the heated plate, inclination angle (0, 10, 20 and 30 ˚), bubble flow rate (100 ml/min) and heat flux (1480 W/m^2). The results showed that micro-bubble swarm played a significant role along a vertical plate caused by mixing of warm liquid, increase in liquid velocity fluctuation and generation vortex near the wall. Ratio of heat transfer coefficient was increased versus increased angle of inclination. The ratios of heat transfer enhancement with bubble to that without bubbles were (3.0 to 5.0).

2. EXPERIMENTAL WORKE

The experimental rig was designed and constructed to investigate water flow parameters in the upward vertical mounted tube at different flow rates subjected to uniform heat flux. The experimental apparatus is shown photographically in Figure 1 and diagrammatically in Figure 2.The test rig consists of the following items:

2.1 Test Section

The test section is a circular cross section channel manufactured from copper**.** The inside and outside diameters of the test section are (50 mm) and (53 mm) respectively. Test section length is (0.7 m). Circular holes of (d=8 mm) are drilled in the surface of the tube. These holes are sealed by plugs of (d=8 mm) for penetration of thermocouple wires, pressure sensor and electric electrodes. The remained penetration areas are covered by silicon that withstands 200℃. The outer tube surface was heated electrically using an electrical heater. The heater consists of two nickel-chrome wires of (1mm) in diameter (3m) length. The electrical wire was wrapped along its length around test section. The maximum power in each wire was (3000 W) ensuring total power of (6000 W). The bare wires of the heater are electrically insulated by ceramic beads. The heater is supplied with AC- current from voltage regulator. The circuit is connected to digital voltage regulator to control the current according to the desired heat flux. Clamp meter is used to measure the current passing through the heater. The heater is covered by a (2 in) layer of fiberglass that withstands (700-850°C) to ensure a reliable insulation for the heater and to concentrate the generated heat in the water flowing inside test section. Aluminum plate covers the material .The temperature inside the test section is measured by thirty five thermocouples type K (chromium - aluminum) distributed within seven sections along the length of copper pipe. The thermocouples are installed in equal space of (10 cm) distances at seven positions. Additional thermocouples are installed inside the tube to measure water temperatures in the inlet and the outlet of the pipe as shown in Figure 3.The end of thermocouple wires connected with standard male plug in order to connect them with the digital thermometer. The test section is connected from its lower end to water flow meter Borden gage and water pump, while the upper part of the test section is connected to Borden gage and then to heat exchanger. The bubble generation inside the test section during the ionization of water is ensured by ionization electrodes .Hydrogen and oxygen bubbles are generated from electrolysis of water. Hydrogen and oxygen bubbles injections in the flowing water are realized using electrodes of (7 cm x 0.7cm x 0. 2cm) dimension plates. The immersed plates in the flowing water are made of copper. Six plates, three anodes and three cathodes were used in the experiments, see Figure 4. The plates were covered by insulation material to prevent direct contact with the pipe**.**

2.2 Heat Exchanger (Double Pipe Helical Coil)

Double pipe heat exchanger manufactured from copper was used in the present experiments. It consists of one pipe placed concentrically inside another pipe with larger diameter. The dimensions of the inner diameter and outer diameter are 1.6 cm and 2.3 cm respectively. The length of tube is 6m.

2.3 Pump

The water flowing in the circuit is divided between the test section and the bypass pipe. The purpose of the bypass pipe is to control water flow rate and pressure in the test section through a control valve. Another line is used in the circuit of heat exchanger to control the temperature of water enters test section.

2.4 Tank Supply Liquid Water

A water tank of (37 liter), dimension (33x53x43) cm and (0.5 cm) plate thickness, was placed at the same level of centrifugal pump and connected to the cold water inlet which was supplied from the water line in Laboratory.

2.5 Pipes and Valves

Polyvinyl chloride (PVC) pipe of (1/2 in) diameter was used to connect the parts of the system. The system consists of four valves.

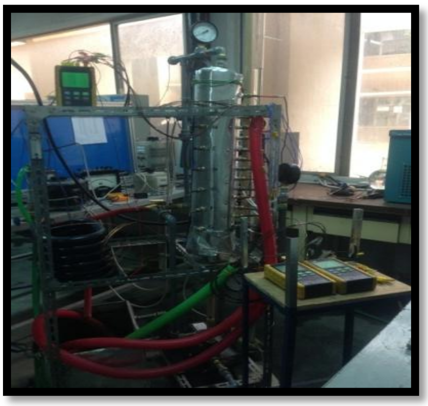


Fig. 1: Photograph of Experimental Apparatus

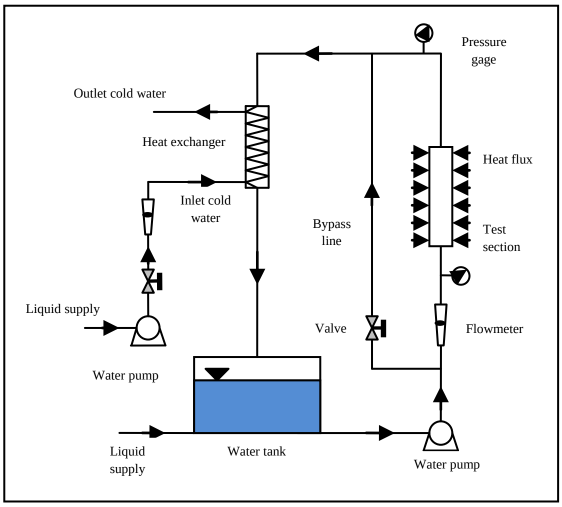


Fig. 2: Schematic Diagram of the Experimental Apparatus

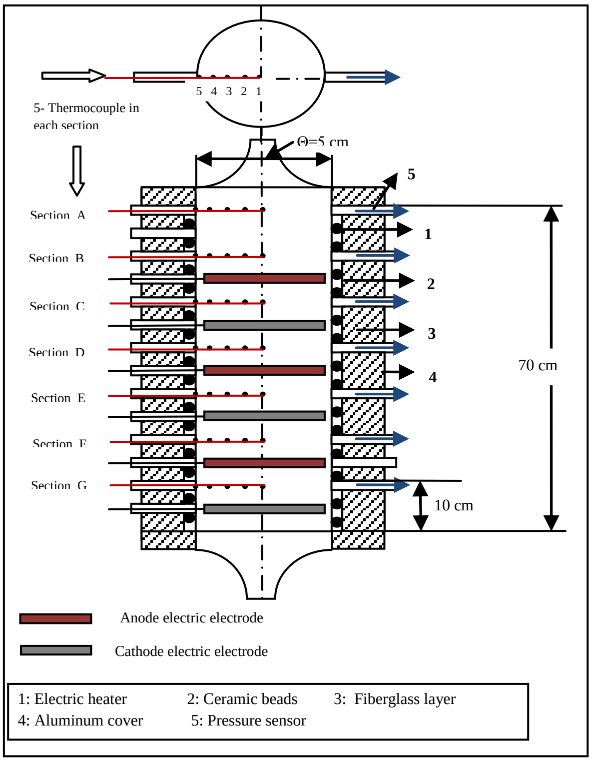


Fig. 3: Test section layout showing the electrical electrodes (Cathode &Anode)

Fig. 4: Copper plate of (7 cm x 0.7cm x 0. 2cm) Dimensions

3. HEAT TRANSFER CALCULATUION

3.1 Heat Flux

The net heat flux is determined from recording the electrical power supplied to the heater and applying the following equation, Salman and Mohammed [15]:

$$Po = I.\,Vo \tag{1}$$

The convection heat transferred from the heated wall of tube:

$$\emptyset_{conv} = Po - \emptyset_{loss} \tag{2}$$

Where:

$\emptyset_{loss}$ is the total conduction heat losses and radiation lasses. It is calculated from:

$$\emptyset_{losses} = \emptyset_{cond} + \emptyset_{rad} \tag{3}$$

$\emptyset_{radiation}$ is very small, so it can be neglected.

$$\emptyset_{loss} = \frac{T_{wall} - T_{alminume}}{\frac{\ln\frac{r2}{r1}}{2\pi k_{pipe} L} + \frac{\ln\frac{r3}{r2}}{2\pi k_{in.1} L} + \frac{\ln\frac{r4}{r3}}{2\pi k_{in.2} L} + \frac{\ln\frac{r5}{r4}}{2\pi k_{almunum} L}}$$

(4)

The convection heat flux can be represented by:

$$q" = \frac{\emptyset_{con}}{A_s} \tag{5}$$

Where: $A_s = \pi \times D_i \times L$

The bulk temperature profile along the length of tube could be represented by the following equation:

$$T_{b2}(x) = T_{b1} + \frac{q" px}{\dot{m} cp} \tag{6}$$

The local heat transfer coefficient is expressed as follows:

$$h(x) = \frac{q"}{(T_{wall\ (x)} - T_{b2(x)})} \tag{7}$$

Average heat transfer coefficient

$$h = \frac{1}{x}\int_0^x h(x)dx \tag{8}$$

Local Nusselt number is calculated using following equation:

$$Nu(x) = \frac{h(x)Di}{\lambda} \tag{9}$$

Average Nusselt number

$$Nu = \frac{1}{x}\int_0^x Nu(x)dx \tag{10}$$

The Reynolds number can be defined according to the particle diameter and the fluid velocity at the inlet as:

$$Re = \frac{\rho u D_i}{\mu} \tag{11}$$

3.2 Rate of Bubbles of Hydrogen and Oxygen

Rate of total bubbles (hydrogen and oxygen) by water electrolysis is defined by**,** Hara et al., [10]:

$$Q_{(H_2+O_2)} = \frac{3IRT_{\infty}}{4BFP} \tag{12}$$

The rate of hydrogen bubbles or oxygen bubbles production is given by**,** Kitagawa et al. [4]:

$$Q_{bubbles} = \frac{IRT_{\infty}}{BFP} \tag{13}$$

3.3 Volume Fraction

Void fraction in a gas-liquid flow may be defined as**,** Kitagawa et al.[4]:

$$\alpha = \frac{Q_{bubble}}{Q_{water} + Q_{bubble}} \tag{14}$$

4. CFD SIMULATION FOR SINGLE PHASE FLOW

The mathematical model for single phase is solved numerically by using a CFD Code Fluent (Ansys15) and Gambit 2.2.30. The energy, momentum and continuity equations are used to describe the motion of laminar flow. The water is used as working fluid. In the present work, the number of nodal points are taken equal to a unique value of (n=31,m=201) as shown in Figure 5. Boundary conditions according to experimental and consist of flow inlets, exit boundaries, wall, and symmetry. The value of velocity of water at the inlet changes for different cases. The outlets of flow are defined as zero gradients. At the walls constant heat fluxes are used.

5. RESULTS

5.1 Results of Single-Phase Flow

Figure 6 shows numerical and experimental results of bulk temperature variation with dimensionless length of cylinder with different values of water flow rates. The results related to low heat flux of (13641 W/m^2) are shown in Figure 6a and those related to high heat flux of (22736 W/m^2) are shown in Figure 6b.The distribution of temperature along the centerline of the fluid starts rising linearly for any value of flow rate in numerical and experimental results and decreases with increasing water flow rate. The deviation between the numerical and experimental results at water flow rate (2, 3 4 lit/min) are (3.7%, 7.24% , 8.4%) at heat flux (13641 W/m^2) and (5.4%, 6.1% and 7%) at heat flux (22736 W/m^2) .

Figure 7 shows numerical and experimental results of wall temperature variation with dimensionless length of cylinder with different values of water flow rates and heat fluxes. It is obvious from these figures that the increase of mass flow rate of water decreases wall temperature .So that, this figure reveals that the wall temperature increases with the increasing of the heat flux. The distribution of wall temperature increases starting from tube entrance. It has been also, observed that, the wall temperature values for high flow rate of water are lower than for low water flow. The main conclusion from the figures showed that, wall temperature obtained from experimental results is higher than from these based on theoretical results. The deviation of the results related to the differences between the numerical and experimental results at water flow rate (2, 3 and 4 lit/min) are (26.24% ,30.5% and 38.8% ,) at heat flux (13641 W/m^2) and (51.7%, %, 56.1, and % 62.1,) at heat flux (22736 W/m^2) .

Figure 8 shows numerical and experimental results of local

Nusselt number variation with dimensionless length of tube with different values of water flow rate and heat fluxes. The local Nusselt number increases due to temperature gradient (surface to bulk) increases with increasing water flow rate and heat flux rate. Furthermore, it reveals that the high value of local Nu number near the inlet of the tube and then it decreases with the increase in the dimensionless length of tube. The local Nux number at the higher heat flux is slightly higher than the results related to lower heat flux. However different heat fluxes showed same trend in shape for local Nux.

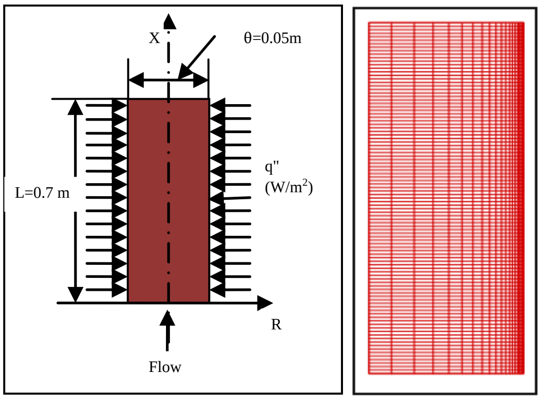


Fig. 5: Geometry of Pipe and Mesh in Two Dimensions

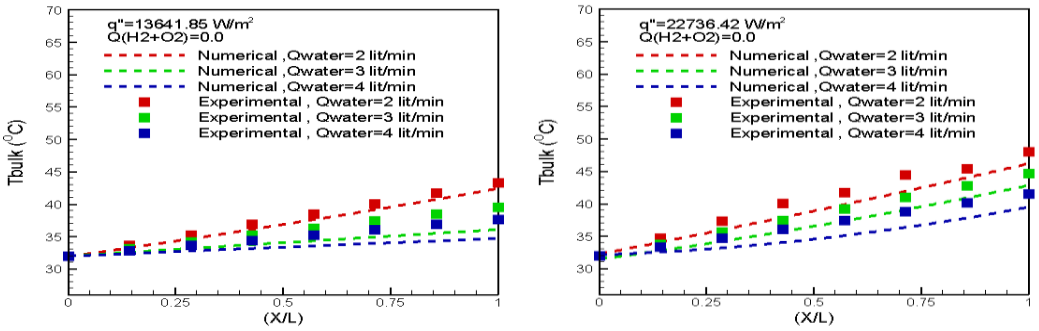
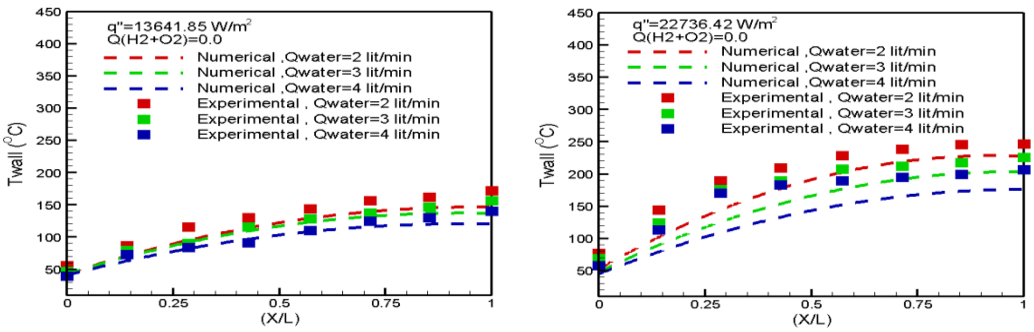
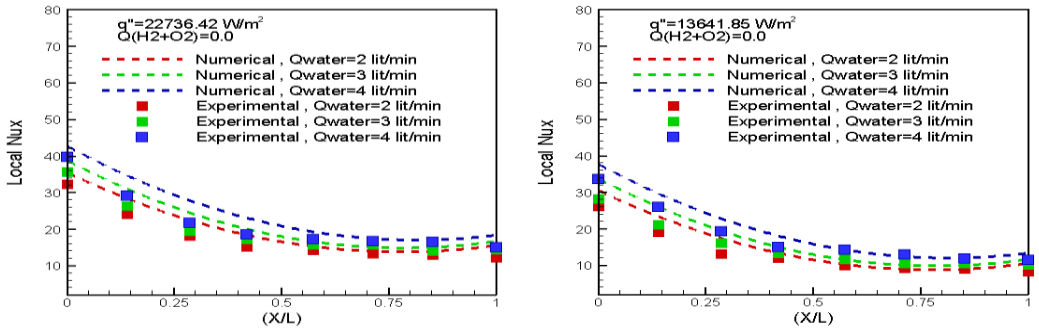


Fig. 6: Comparison of numerical and experimental results of bulk temperature variation with length of tube at different values of heat fluxes



(a) q"=13641 W/m^2 **(b) q"=22736 W/m^2**

Fig. 7: Comparison of Numerical and Experimental Results of Wall Temperature Variation with Length of Tube at Different Values of Heat Fluxes



(a) q"=13641 W/m^2 **(b) q"=22736 W/m^2**

Fig. 8: Comparison of Numerical and Experimental Results of Local Nusselt Number with Length of Tube at Different Values of Heat Fluxes

5.2 Results of Hydrogen and Oxygen Bubbles Injection – Water

Figure 9 shows experimental results of bulk temperature variation with dimensionless length of tube with different value of water flow rates (2,3 and 4 lit/min) , heat fluxes (13641 W/m^2 , 22736 W/m^2) and bubbles flow rates (0.020 , 0.025 lit/min). It could be seen from the figures that for increase range of heat flux, the bulk temperature increases. Also, bubbles injection causes mixing of flow from center to wall, and rises in the upward direction inside water column as the density of bubbles (0.0899 kg/m^3) is much less in comparison to water density (1000 Kg/m^3). This leads to increase bulk temperature along the tube length. Figure 10 shows experimental results of wall temperature variation with dimensionless length of tube with water flow rate of (2 lit/min) and heat flux of (13641 W/m^2 and 22736 W/m^2). It is obvious that wall temperature increases along tube length and it increases with increasing heat flux value. Bubbles flow rate is one of the import variables that effect on wall temperature. The wall temperature decreases significantly because of bubbles concentration near the wall and that thermal conductivity of the bubbles is less than that of water. Figure 11 shows experimental results of local Nusselt number variation with tube dimensionless length at different water flow rate, heat flux and bubbles flow rate values. Local Nusselt number decreases with the increase in x distance along tube length .The local Nusselt number decreases due to temperature gradient increases with water flow rate decreases and heat flux rate increases. Furthermore, it reveals that the highest value of local Nu number occupies the position near the test section inlet. It could be seen from the figures that the same shape for local Nux for different heat fluxes was observed. It is noted also that as bubbles concentration increases it causes an increase in local Nu number value.

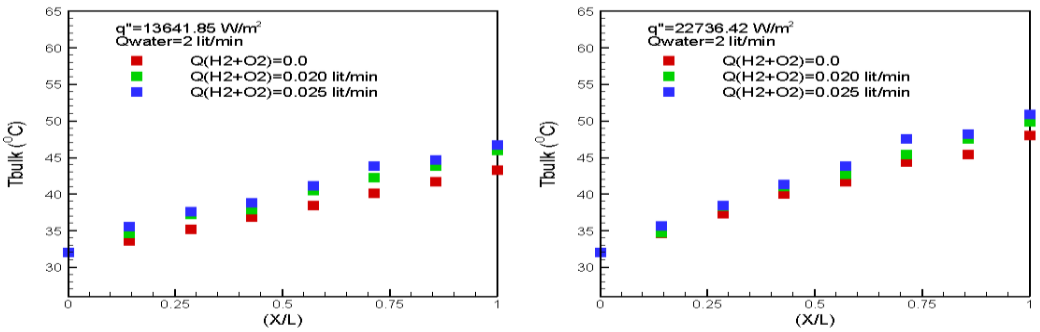
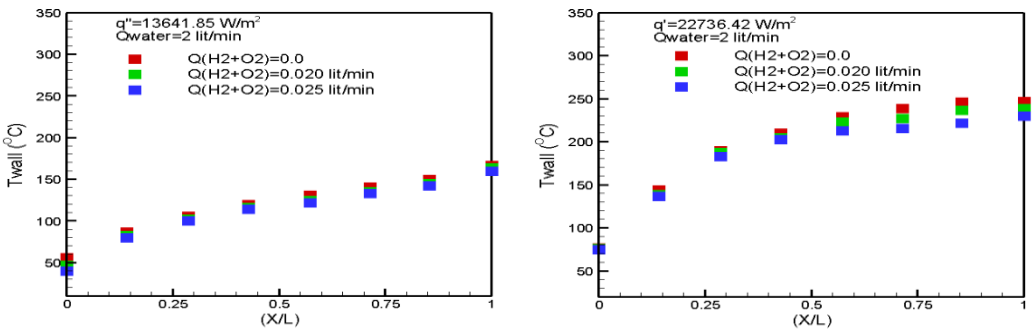
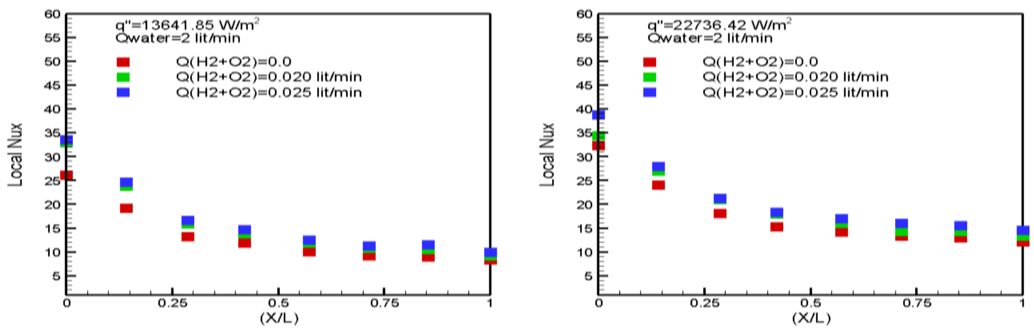


Fig. 9: Experimental Results of Bulk Temperature Variation with Length of Tube for different Values of Bubble Flow Rates and Heat Fluxes



(a) q"=13641 W/m^2 **(b) q"=22736 W/m^2**

Fig. 10: Experimental Results of Wall Temperature Variation with Length of Tube for different Values of Bubble Flow Rates and Heat Fluxes



(a) q"=13641 W/m^2 **(b) q"=22736 W/m^2**

Fig. 11: Experimental Results of Local Nusselt Number Variation with Length of Tube for Different Values of Bubble Flow Rates and Heat Fluxes

Figure 12 shows the experimental results of local Nusselt number normalized values with bubbles injection to those without bubbles injection, Nuxo/Nux at different X/L and water flow rate of (2 lit/min) and heat fluxes of (13641 W/m^2 , 22736 W/m^2) . The ratio of local Nusselt number increases with bubble flow rate increases and this increase is high in low heat flux (13641 W/m²) in comparison to high heat flux (22736 W/m²).

Figure 13 shows the experimental results of average Nu variation with Re number at different values of heat flux and $Q_{(H2+O2)}$. The average Nu number, increases with increasing in the Reynolds number. It is noted also that bubbles flow rate increases leads to increase in average Nusselt number.

Figure 14 shows experimental results of average Nusselt number ratio with bubble injection to that without injection Nuxo/Nux versus Re number at different heat fluxes and $Q_{(H2+O2)}$ values. The ratio of Nusselt number increases with decreasing heat flux and increasing bubbles flow rate. The Nusselt number ratio decreases also with Reynolds number increase. It is noted also that the enhancement ranges from (1.04 to 1.26).

5.3 Verification of the Results

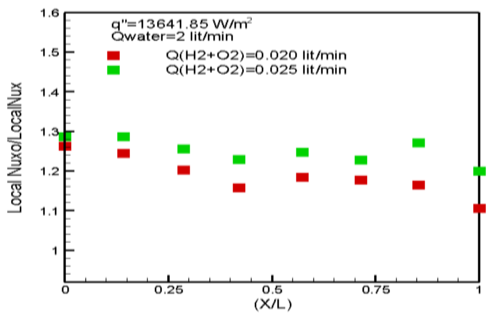
5.3.1 Comparison with Previous Studies for Single Phase Flow

Figure 15 shows the effect of varying the mesh size on the local Nux number. A grid independency test is preformed to check the validity of the numerical technique. For single phase flow, more published experimental and numerical data available for air injection into vertical pipe, vertical annular, water in horizontal pipe for fully developed reign and boundary condition under constant wall temperature or constant heat flux. Therefore, the better research to compare the result of the experimental present work for Re=1214 and q"=13641 W/m^2 with, He et al., [16] was carried out for Re=1500 and q"=8199 W/m^2 are shown in Figure 17.Also, experimental results of present work for pure water compared with Shah equation for laminar flow under constant heat flux.

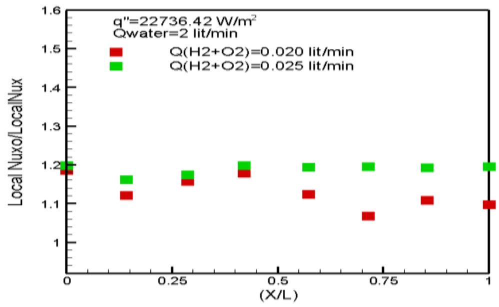
Shah equation for laminar flow:

$$Nu = \begin{cases} 1.953\left(RePr\frac{D}{X}\right)^{1/3} & \left(RePr\frac{D}{X}\right) \geq 33.3 \\ 4.364 + 0.0722RePr\frac{D}{X} & \left(RePr\frac{D}{X}\right) \leq 33.3 \end{cases} \quad (15)$$

Wall temperature for single phase flow is compared also with the numerical and experimental results of the, Celata et al.,[17] as shown in Figure 16.



(a) q"=13641 W/m^2



(b)q"=22736 W/m^2

Fig. 12: Experimental results of local Nuxo/Nux variation with X/L at different value of heat flux and bubble flow rate

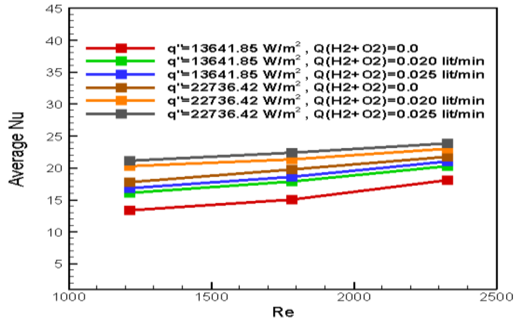


Fig.13: Experimental results of average Nu number variation with Re number for different values of heat fluxes and $Q_{(H2+O2)}$

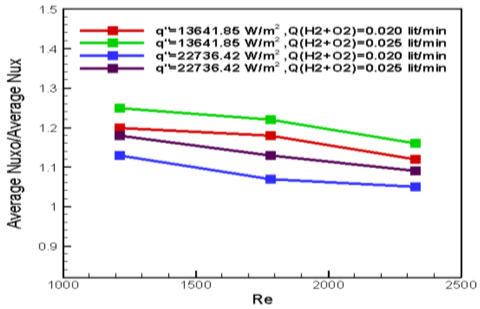


Fig. 14: Experimental results of ratio of average Nuo/Nu variation with Re number for different values of heat fluxes and $Q_{(H2+O2)}$

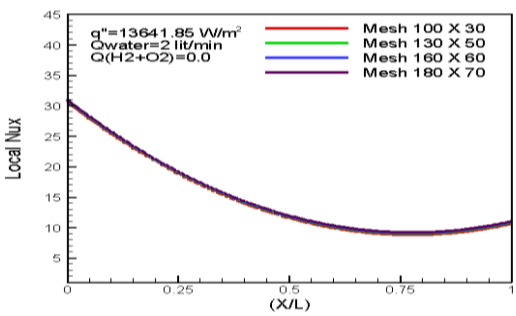


Fig. 15: Effect of Mesh Size on the Local Nux Number for Single Phase flow

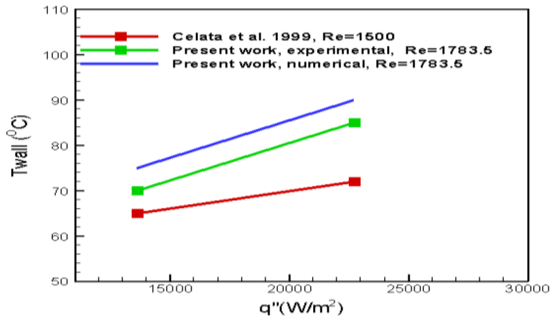


Fig. 16: Comparison of the Wall Temperature for the Present Work for Single Phase Flow

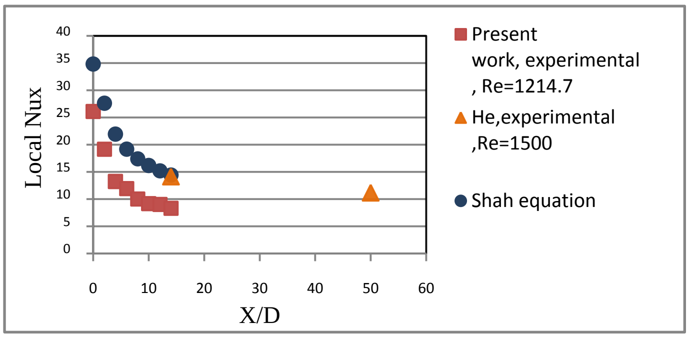


Fig. 17: Comparison of the local Nusselt number for the present experimental study for single phase flow

6. CONCLUSIONS

- Good agreement between experimental and numerical results for the single phase flow was observed and the deviation was due to the influence of losses through experimental test.
- The value of local Nusselt number was significantly influenced by the bubbles from water electrolysis along length of pipe.
- The ratio of enhancement in average Nusselt number increased from (1.04 to 1.26) by water electrolysis bubbles.
- The ratio of local Nusselt number increased with increasing bubble flow rate and this increase was high in low heat flux (13641 W/m²) in comparison with high heat flux (22736 W/m²).
- It is clear from the two phase results, the enhancement in Nusselt number decreased with increasing heat flux.
- A reduction in wall temperature along test section by injection bubbles increased with increasing rate of bubbles injection.
- Ratio of average Nusselt number with bubble injection to that without injection Nuxo/Nux decreased with increasing Reynolds number.

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8. NOMENCLATURE

Latin Symbol

D_i = tube inner diameter, m

F = faraday constant, ($F=9.65\times10^4$ A·s/mol)

I = electric current, Am

L = length of pipe, m

Po = electrical power, W

Q_{water}= water flow rate, Kg/s

$Q_{(H2+O2)}$ = total bubble of (hydrogen & oxygen) , Kg/s

q"= heat flux, W/m^2

h = average heat transfer coefficient, $W/m^2.^oC$

hx = local heat transfer coefficient,

Nu = average Nuesslt number, dimensionless

Nux = local Nusselt number, dimensionless

R = universal gas constant, ($R=8.31\times10^9$ kJ/kg .k)

T_{wall} = wall Temperature, ºC

T_{b1} = bulk Temperature at inlet, ºC

T_{b2} = bulk Temperature at outlet, ºC

T_{bulk} = bulk Temperature, ºC

Vo= voltage, Volt

B = number of excess electrons (For H_2=2, O_2=4)

Greek Symbols

α = volume fraction, dimensionless

$\emptyset_{conv}$ = convection of heat transfer, W

$\emptyset_{loss}$ = loss of heat transfer, W

$\emptyset_{cond}$ = conduction heat transfer, W