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# Experimental study of Hydrogen Bubbles Injection Effect on Thermal Boundary Layer for Laminar Water Flow in Vertical Cylinder

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## ABSTRACT
Temperature measurements are performed to clarify the effects of sub-millimeter bubble injection on the thermal boundary layer thickness in water flowing in upward direction along a cylindrical shape 0.7m length and 0.065m diameter test section. The test section is subjected to constant heat flux of (24,000w/$m^2$).

In particular the research focuses on the relationship between the bubble injection rate and their effect on decreasing thermal boundary layer thickness. This effect led to enhance the heat transfer rate and decrease test section wall temperature. Three pairs of bubble injection electrodes are used in the experiments fixed at equally spaced distances of 0.2m between each pair of them. The experiments based on Reynolds number of (6780) which simulates low water velocity for better distinguishing the enhancements governed the experimental results. Water temperature at seven radial positions from test section center to the wall are measured along the test section in addition to the measurement of water bulk and wall temperatures at these points. K-type 100 lm thermocouples with ±0.12°C accuracy are used for temperature measurements. The results showed thermal boundary layer thickness is inversely proportional to the hydrogen injection rate and that local heat transfer coefficient is proportional to the later with different proportionality rates. The results showed maximum percentage decrease of thermal boundary layer of (40%) and maximum percentage increase in heat transfer rate of (15.7%). Accordingly the boiling safety factor based on maximum wall temperature showed maximum increase of (9%). These results covered the adopted values of heat flux, Reynolds number and hydrogen bubble injection rate.

## Keywords
Thermal boundary layer, Hydrogen bubbles, heat transfer coefficient, boiling safety factor

## 1. INTRODUCTION
The range of water velocity used in the recent experiments to study the enhancement in forced convection rates caused by injection of sub millimeters bubbles and its effect on thermal boundary layer thickness is not discussed in previous works according to the authors knowledge. The heat transfer in this range is very close to that related to natural convection. Natural convection heat transfer is widely used in various types of heat transfer equipment. For instance, in recent years, a solar water heater has received a lot of attention because of its efficient energy use, in which the natural convection heat transfer is used at heat-collecting plates. Several useful techniques, such as the use of a heat transfer promoter (e.g., Tsuji et al. 2007) and a bubble injection technique have been proposed with the goal of enhancing natural convection heat transfer. In particular, the bubble-injection technique is considered to be effective when liquid is used as the working fluid. In previous studies, Tamari and Nishikawa (1976) investigated the effects of the injection of air bubbles on the natural convection heat transfer from a vertical heated plate in water or ethanol. Tokuhiro and Lykoudis (1994a, b) performed detailed investigations on the natural convection heat transfer from a vertical heated plate in mercury with nitrogen-bubble injection. Both research groups used bubbles of a few millimeters in diameter and showed that bubble injection is an effective technique for enhancing natural convection heat transfer. More recently, Kitagawa et al. (2009, 2010) investigated flow and heat transfer characteristics of natural convection from a vertical heated plate in water with the injection of sub millimeter bubbles whose diameters were less than the boundary layer thickness in most cases. As a result, it was found that in the laminar region, the ratio of the heat transfer coefficient with bubble injection to that without bubble injection (which is hereinafter called the ‘‘heat transfer coefficient ratio’’) is approximately 2, even when the bubble flow rate Q is less than 60 mm3/s (which is much smaller than the bubble flow rate used in each previous study). Their velocity measurements and numerical simulations revealed that this heat transfer enhancement results mainly from a forced-convection effect caused by bubbles rising at high speed. Similar heat transfer enhancement by sub-millimeter bubbles was observed in the turbulent region (the heat transfer coefficient ratio for Q = 56 mm3/s was 1.2–1.3). The purpose of this study was to clarify effects of sub millimeter bubble injection on the transition to turbulence in the natural convection boundary layer along a vertical cylinder in water.

In particular, the bubble injection position is considered to be an important parameter in this study, and the authors therefore recommends on investigating the relationship between bubble injection position and the transition to turbulence in the natural convection boundary layer.

## 2. EXPERIMENTAL WORK
The experimental test rig is designed and constructed to investigate the effect bubbles injection on heat transfer parameters. The experiments are conducted in upward vertical mounted cylindrical test section subjected to uniform heat flux. The experimental test rig is shown in Figure (1). The test section of the rig is a circular cross section channel manufactured from copper. The inside diameter of the test

section is (0.065m). Water flows inside the test section in the upward direction at flow rate equals (10 liters/ min). Test section length is (0.7m). Circular holes of (d=5mm) are drilled in the surface of the cylinder. These holes are specified for penetration of thermocouple wires, pressure sensor and water ionization electrodes. The outer tube surface is heated electrically using an electrical heater. The heater ensures maximum heat flux of (24,000w/$m^2$). 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 (750°C) to ensure a reliable insulation for the heater and to concentrate the generated heat in the water flowing inside test section. The temperature along the test section wall and bulk water is measured by fourteen thermocouples type K (chromium - aluminum) distributed within seven positions along the length of copper pipe. Water temperature adjacent to the pipe wall along its radius is measured using calibrated thermopiles. The thermopiles are installed in equally spaced (10 cm) distances at seven positions. Each thermopile consists of seven thermocouples to measure water temperature along the radius of the test section at each position. The distance between thermopile sensors are 0.762 mm which insured coverage distance of 5.3 mm, see Figure (3). The end of thermocouple wires are connected with calibrated digital thermometer. The test section is connected from its lower end to the water inlet tank through circulating water pump. The water that leaves the test rig is drained to the sewer which represents open loop circuit for the purpose of ensuring constant water temperature in the test section inlet. 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. Three pairs of water electrolysis electrodes are used for water ionization. The electrodes are fixed at 0.2m equally distances. First pair is fixed at 0.2m from test section entrance. Five amperes 24 volts are ensured for ionization purpose using current supply device. Figure (2) shows sub-millimeter-bubbles injection and temperature measurement taps. The power supply (voltage regulator) is connected in parallel to the AC digital voltage control to cross check circuit voltage. Calibrated multi-meter is used to measure ionization circuit current in amperes. Digital voltage is connected to the circuit to measure voltage passing through electrodes.

## 2.1 Measurement system

The measurement system consists of the following items:

- Voltage regulator (variance) is connected to the power supply for the purpose of adjusting the power input rate of the heater as required. A digital voltmeter is linked to the circuit in parallel with heater element to measure heater voltage.
- Hydrogen bubbles generation circuit consists of voltage regulator device (variance) and two multi-meter. The digital device is used to measure the current and the analogue device is used to measure the output voltage from Variance.
- Digital watt meter is used to measure the heater power directly.
- Clamp multi-meter is used to measure the current passes through the heaters for cross checking.

## 2.2 Measurement Procedure

Before each test, the test rig is cleaned with water then all connections are checked. The thermocouples are checked and connected to the data logger. The water pump is operated and tap water is circulated through different parts of the system. The electrical power is switched on, and the heater input voltage adjusted by the voltage regulator to ensure the required voltage and current. The supplied voltage and current to the heater were recorded to calculate the required electrical power in accordance to the required heat flux. The temperature of the water at the copper tube inlet is fixed at (25℃) during all the experiments. Following parameters are recorded after insuring steady state condition: Water temperature at pipe inlet, Thermocouples readout of water bulk and wall temperatures at seven positions along the test section, Thermopiles read out at thirty five positions adjacent to pipe wall located along the pipe length and radius. Water flow rate inside the pipe, Water pressure at inlet, outlet and seven points located along the pipe, Heater power using watt meter connected to the heat source circuit. Water volumetric flow rate is fixed at 10 liter/min equivalent to ($1.67 \times 10^{-4}$ $m^3$/s).

# 3. MATHEMATICAL APPROACH

The following principal equations are used to estimate heat transfer coefficient distribution and boiling safety factor along the test section:

The convection heat flux can be represented by:

$$q" = \frac{\emptyset_{conv}}{A_s} \quad (1)$$

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

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

$$T_{b2}(x) = T_{b1} + \frac{q"px}{\dot{m}cp} \quad (2)$$

The local heat transfer coefficient is expressed as:

$$h(x) = \frac{q"}{(T_{wall\ (x)} - T_{b2(x)})} \quad (3)$$

Local Nusselt number is calculated using following equation:

$$Nu(x) = \frac{h(x)Di}{k} \quad (4)$$

$$Nu(x) = c\left(Re(x)\right)^n . Pr^m \quad (5)$$

Where C, m and n are factors depends on the geometry of the channel, type of fluid, boundary condition and Reynolds number.

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

$$Re = \frac{\rho u D_i}{\mu} \quad (6)$$

Where u is water velocity,

$$u = Q/A_f \quad (7)$$

Sub-cooled nucleate boiling of the coolant starts the heat source clad surface temperature reach to the boiling temperature at that position, $T_B$. The followingg correlation is used for $T_B$ estimation;

$$T_B = T_{sat.} + 2.03 \text{ x } q''^{0.35} \text{ x } P^{-0.23} \quad (8)$$

Where:

$T_B$ = Sub-cooled nucleate boiling temperature (℃).

$T_{sat.}$ = Saturated temperature of the coolant given based on certain pressure.

$$P = P_i + \rho \times g \times z + \left(f \frac{z}{D_h}\right) \times \left(\frac{u^2}{2 \times g}\right) \qquad (9)$$

Where:

P = Coolant pressure at the position of maximum clad temperature (bars).

$P_i$ =Inlet pressure at the bottom of the channel equals circulation pump outlet pressure.

($N/m^2$) f =friction factor= $\frac{Re^{0.25}}{64}$ (10)

To avoid sub-cooled nucleate boiling at clad surface, the maximum clad temperature at the hot spot shall be lower than boiling temperature. Safety factor (K) given by the following equation, K used to estimate this temperature:

$$K = (T_{Bo} - T_{in})/(T_w - T_{in}) \qquad (11)$$

Where:

$T_{in}$ = Channel inlet water temperature(45℃).

## 4. RESULTS AND DISCUSSION

Table (1) shows the input parameters based in the experiments. Tables (2&3) show the results of temperature measurement along test section radius at seven positions along its length for both Hydrogen free tests and those with hydrogen injection. Water bulk temperature and test section wall temperature are also tabulated in the same tables. Table (4) shows heat transfer characteristics related to experiments conduction without $H_2$ injection and those based on $H_2$ injection.

Figure (4) shows the effect of Hydrogen bubbles injection on radial temperature distribution at different axial positions. The figure proves that wall temperature decreases axially with bubbles injection while water bulk temperature increases axially with bubbles injection.

The figure proves also that the effect of hydrogen bubbles increases axially due to the increase of the bubbles injection rate versus its length. This effect is clear from figures (4 a-g).

Figure (5) shows that thermal boundary layer thickness is inversely proportional to the hydrogen injection rate. The results show that maximum percentage decrease of thermal boundary layer of (40%). Thermal boundary layer decrease affected the heat transfer rate positively due to the turbulence effect accompanied this phenomena.

Figure (6) shows the effect of bubbles injection on water bulk temperature which increases with bubbles injection due to the effect of water mixing within thermal boundary layer with bulk water adjacent to it. The percentage of water bulk temperature increases with Hydrogen injection to that with pure water flow reaches 50%.

Figure (7) show the effect of bubbles injection on wall temperature of the test section. It is clear that wall temperature is inversely proportional to bubbles injection rate. Wall temperature shows maximum decrease of (6.1$^o$C) at the end of the test section.

Figure (8) shows the effect of bubbles injection on heat transfer coefficient. It is clear that the tests conducted with pure water flow show inverse proportionality versus test section length while the tests with hydrogen injection shows that heat transfer coefficient is proportional versus test section length. The results show maximum percentage increase in heat transfer rate of (15.7%).

Figure (9) shows the effect of bubbles injection on the boiling safety factor based on test section wall temperature. The boiling safety factor shows maximum increase of (9%) at the end of the test section.

## 5. CONCLUSION

The main target of power generation systems is to increase the heat rejection rate from heated surface to cooling water and also to ensure the integrity of the heated surface by investigating the boiling safety factor at the hottest spot.

Bubbles injection inside upward flow cooling channel subjected to constant heat flux prove an enhancement in heat transfer rate. Both above targets are realized by increasing water bulk and decreasing test section wall temperature.

The results show that maximum percentage decrease of thermal boundary layer of (40%). The percentage of water bulk temperature increases with Hydrogen injection to that with pure water flow reaches 50%.

Wall temperature shows maximum decrease of (6.1$^o$C) at the end of the test section. The results show maximum percentage increase in heat transfer rate of (15.7%).

The boiling safety factor shows maximum increase of (9%) at the end of the test section. The author recommends investigating the effect of coolant flow rate and heat flux rate on the results and findings as future work. In addition the author recommends investigating the effect of bubble injection rate and position on the transition to turbulence in the natural convection boundary layer.

## 6. NOMENCLATURE

$A_s$ = surface area, $m^2$

$A_f$ = Flow area. $m^2$

$D_i$ = tube inner diameter, m

g = gravitational acceleration, $N/m^2$

L = length of pipe, m

P = pressure, Pa

Po = electrical power, W

Q = water flow rate, Kg/s

q"= heat flux, $W/m^2$

m = mass flow rate, kg/s

Cp = Water heat capacity, J/kg. $^o$C

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

hx = local heat transfer coefficient,

Nu = average Nuesslt number, dimensionless

Nux = local Nusselt number, dimensionless

Re = Reynolds number

$T_{in}$ = inlet temperature, ºC

$T_w$ = wall Temperature, ºC

$T_B$ = bulk Temperature at inlet, ºC

$T_{sat}$ = Saturation temperature, $^{o}C$

$T_{bo}$ = Boiling tmeperature, $^{o}C$

$\delta_{th}$ = Thermal boundary layer thickness, mm

## 7. ACKNOWLEDGEMENT

The author acknowledges both University of Baghdad and American University – Madaba in Jordan for their assistance to conduct this research.

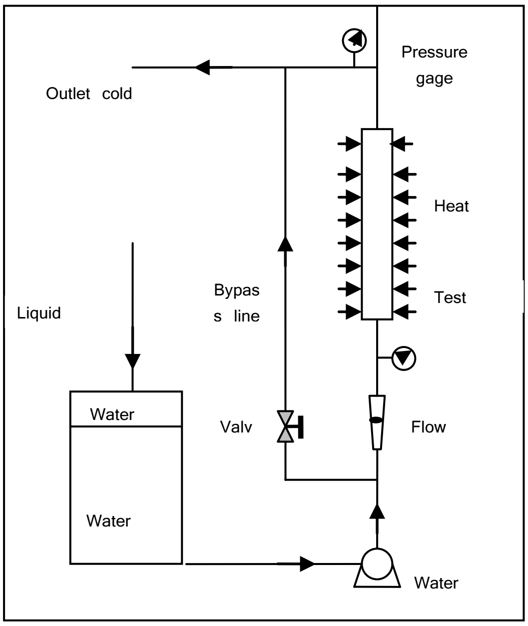



**Fig (1-A): Experimental test rig layout**

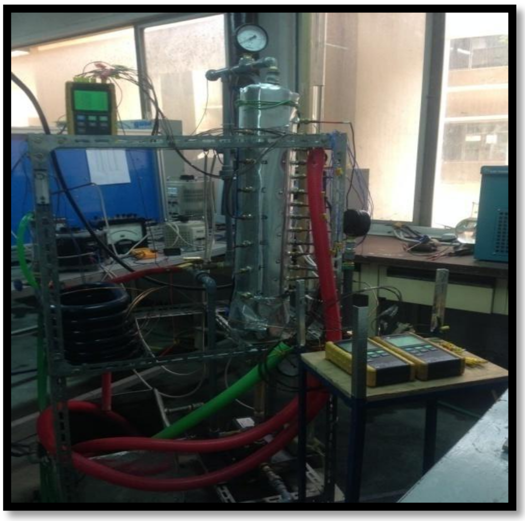
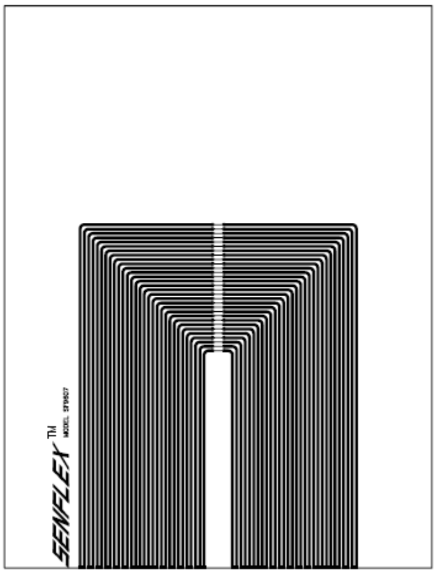


**Fig (1-B): Photograph for experimental test rig**

**Fig (2): Sub-millimeters bubbles injection system and temperature measurement taps**




Array No. SF9607: 30 elements, 0.03 inch (0.762 mm) spacing.

**Fig (3): Thermopile used for temperature measurement along test section radius**

**Table (1): The Range of the Measured Variables**

| Parameters | Values |
|---|---|
| Inlet water temperature | 25°C |
| outlet water temperature without hydrogen bubbles | 30°C |

| | |
|---|---|
| Maximum surface temperature without hydrogen bubbles | 93.4°C |
| outlet water temperature with hydrogen bubbles | 32.5°C |
| Maximum surface temperature with hydrogen bubbles | 87.3°C |
| Water flow rate | (10) l/min |
| power | 3430 W |
| Heat flux | 24,000 W/m$^2$ |
| Heat transfer coefficient, at maximum surface temperature without hydrogen bubbles | 399.4 w/m$^2$.°C |
| Heat transfer coefficient, h at maximum surface temperature with hydrogen bubbles | 418.8 w/m$^2$.°C |
| Inlet water pressure | 1.165 bar |
| Outlet pressure | 1.1 bar |
| Ionization Voltage, Volts | 24 |
| Ionization Current, Amps | 5 |

**Table (2): Temperature measurement results along test section radius and length without $H_2$ bubbles**

| Test section Length, m | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
|---|---|---|---|---|---|---|---|
| $T_B$ | 25.7 | 26.4 | 27.1 | 27.8 | 28.5 | 29.2 | 30 |
| $T_1$ | 25.7 | 26.4 | 27.1 | 27.8 | 28.5 | 29.2 | 30 |
| $T_2$ | 25.7 | 26.4 | 27.1 | 27.8 | 28.5 | 30.9 | 36.6 |
| $T_3$ | 25.7 | 26.4 | 27.1 | 27.8 | 35.7 | 41.2 | 46 |
| $T_4$ | 25.7 | 26.4 | 30 | 39.1 | 49.9 | 51.5 | 55.5 |
| $T_5$ | 25.7 | 32.6 | 44.4 | 52.1 | 58.1 | 61.8 | 65 |
| $T_6$ | 33.5 | 44.8 | 58.8 | 65 | 69.4 | 72 | 75.6 |
| T7 | 59.9 | 63.8 | 73.2 | 78.1 | 80.6 | 82.3 | 83.7 |
| $T_w$ | 86.2 | 86.9 | 88.9 | 91.1 | 91.8 | 92.6 | 93.4 |

**Table (3): Temperature measurement results along test section radius and length with $H_2$ bubbles**

| Test section Length, m | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
|---|---|---|---|---|---|---|---|
| $T_B$ | 25.7 | | 27.6 | | 30 | | 32.5 |
| $T_1$ | 25.7 | | 27.6 | | 30 | | 32.5 |
| $T_2$ | 25.7 | | 27.6 | | 30 | | 32.5 |
| $T_3$ | 25.7 | | 27.6 | | 30 | | 32.5 |
| $T_4$ | 25.7 | | 27.6 | | 30 | | 47 |
| $T_5$ | 25.7 | | 27.6 | | 40.5 | | 60.8 |
| $T_6$ | 33.5 | | 52.4 | | 58.6 | | 72.2 |
| T7 | 59.9 | | 68.7 | | 77.5 | | 81.2 |
| $T_w$ | 85 | | 85.5 | | 86.2 | | 87.3 |

**Table (3): Heat transfer characteristics of the fluid flowing in the upward direction inside vertically mounted test section**

| Test section Length, m | | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 |
|---|---|---|---|---|---|---|---|---|
| h, w/m$^2$.°C | Without $H_2$ | 396.7 | 396.7 | 388.3 | 379.1 | 379.1 | 378.5 | 378.5 |
| | With $H_2$ | 404.7 | | 414.5 | | 427.0 | | 438.0 |
| K | Without $H_2$ | 1.38 | 1.36 | 1.32 | 1.27 | 1.25 | 1.23 | 1.22 |
| | With $H_2$ | | | 1.39 | | 1.36 | | 1.39 |
| $\delta_{th}$, mm | Without $H_2$ | 1.75 | 2.6 | 3.2 | 3.7 | 4.3 | 4.7 | 5.1 |
| | With $H_2$ | | | 2.3 | | 3.05 | | 4.1 |

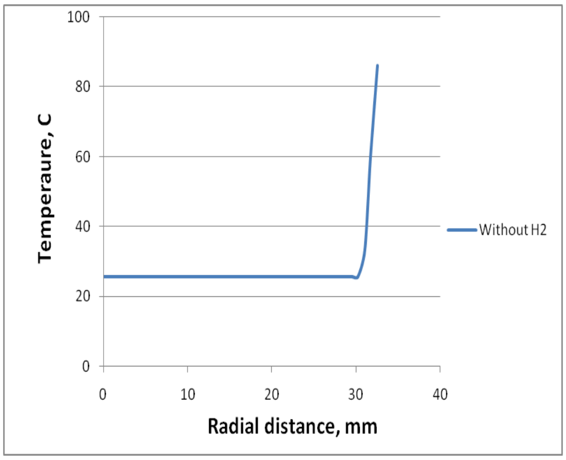



**Fig (4-a)**

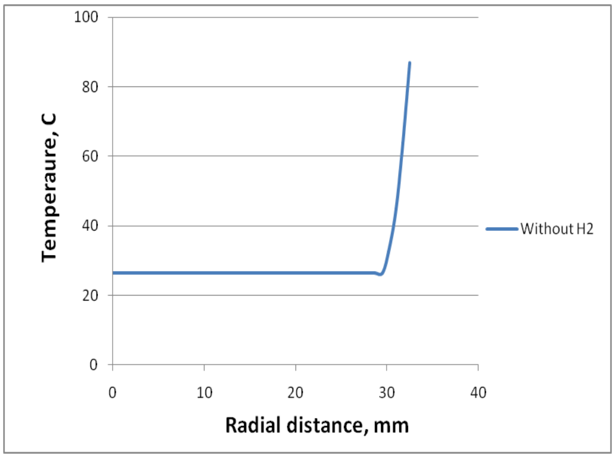



**Fig (4-b)**

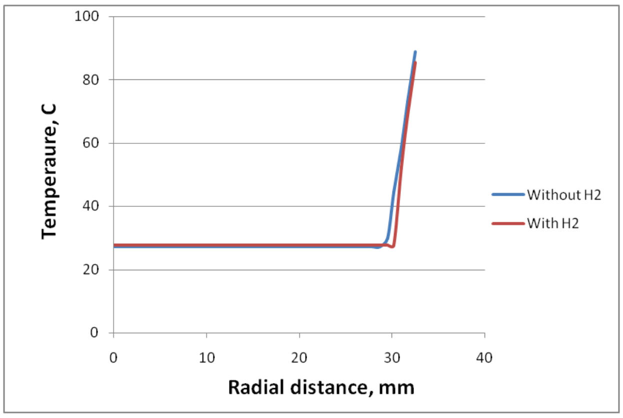



**Fig (4-c)**

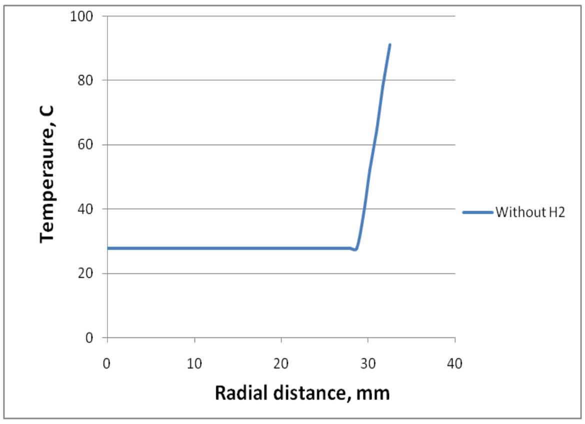



**Fig (4-d)**

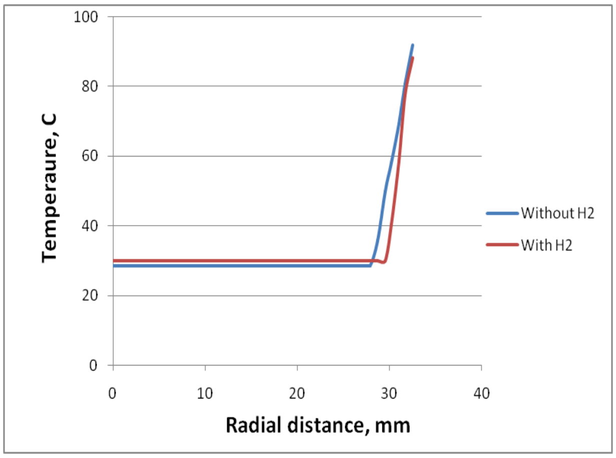



**Fig (4-e)**

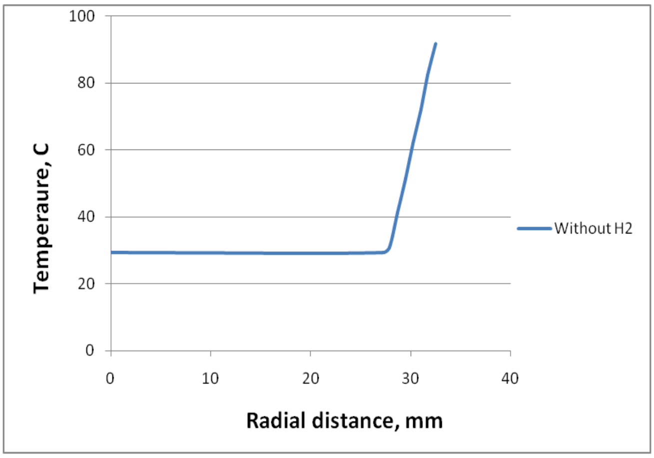



**Fig (4-f)**

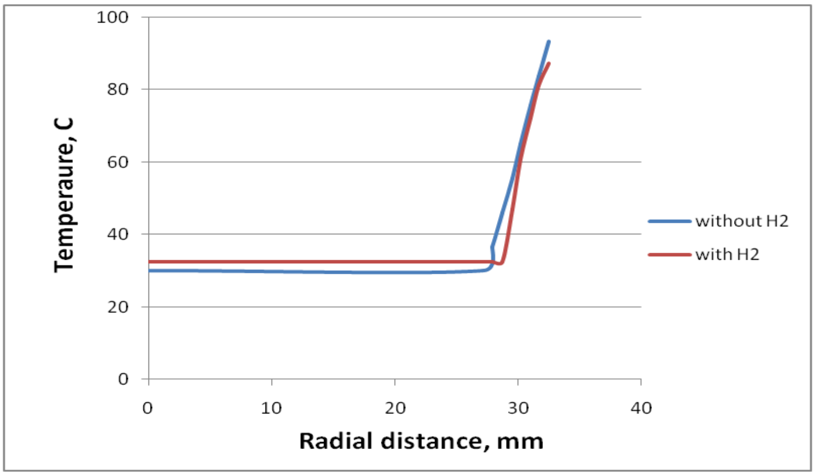
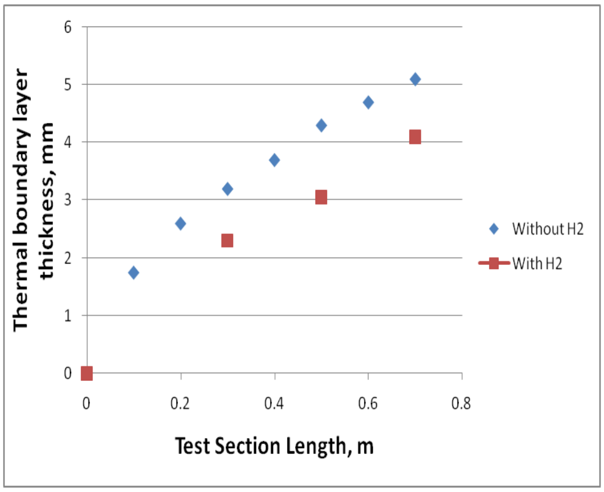



**Fig (4-g)**

**Figure (4): Radial temeprature distribution across test section radius starting from channel center, (a) at axial length =0.1m, (b) at axial length =0.2m, (c) at axial length =0.3m, (d) at axial length =0.4m, (e) at axial length =0.5m, (f) at axial length = 0.6m, (g) at axial length =0.7m**



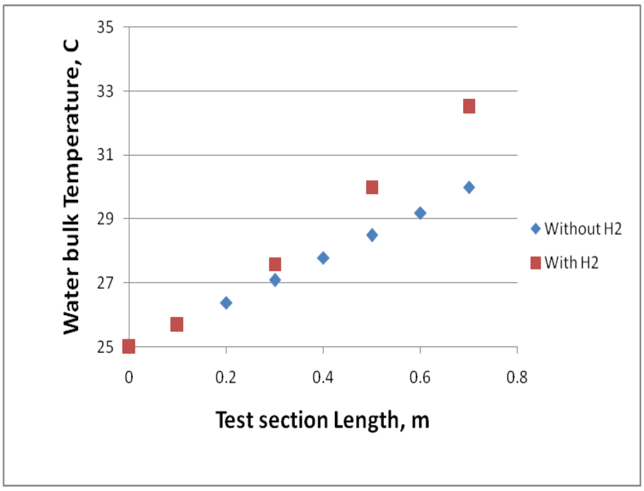
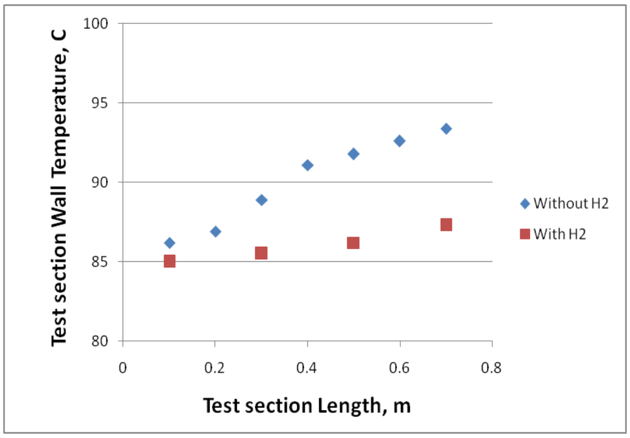




**Fig (5): Thermal boundary layer thickness Fig (6): Water bulk temperature distributionalong test section length along test section length**



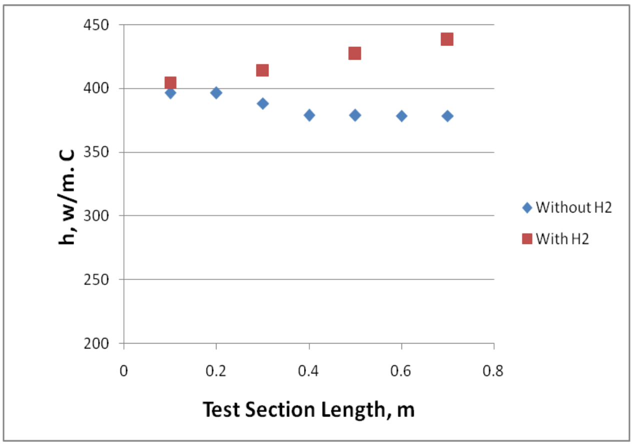




**Fig (7): Wall temperature distribution along Fig (8): Local heat transfer coefficient, halong test section length distribution along test section length**

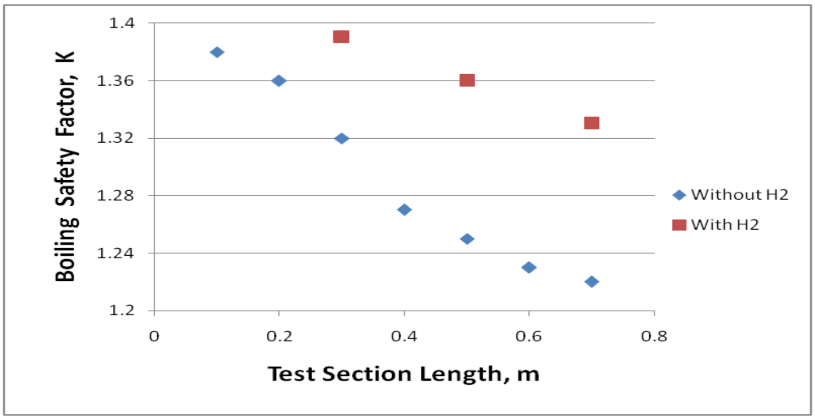



**Fig (9): Boiling safety factor, K distribution along along test section length**

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