FLASH EVAPORATION ENHANCEMENT BY ELECTROLYSIS OF SATURATED WATER FLOWING UPWARDS IN VERTICAL PIPE

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ABSTRACT

An experimental system was designed and built to produce the flash evaporation of upward water flow in a (1.8 m) vertical mounted glass test section pipe. The water loses the static head as it moves up, accordingly flash evaporation occurs somewhere inside the test section, where the water local temperature reaches its saturation temperature at that position, which is dependent on the water inlet temperature and its mass flow rate. The steam quality in the test section exit was measured by collecting the steam generated in the test section outlet and condensed in the condenser at specified time.

The hydrogen bubbles are injected inside the two – phase mixture flow within the test section. These bubbles act as an exciter for steam generation inside saturated water.

Water electrolysis using (12 V) and ionization current (7 A), increases steam quality at test section outlet by (33%) when it is compared to that obtained without water electrolysis. A reduction of (42%) in non-equilibrium temperature difference is achieved using the same ionization settings. The effect of ionization process on flash inception point and temperature is investigated from the experiments.

The experimental results are compared to the theoretical results obtained using mathematical model based on solving the mass, momentum and energy equations for two –phase flow assuming separated flow model.

The effect of the electrical power used for water ionization is simply simulated in these calculations using mass and heat balance equation that covers the boundary conditions of the system.

الخلاصة

تم تصميم منظومة تجريبية لغرض تحقيق ظاهرة الغليان التلقائي أثناء جريان الماء إلى الأعلى داخل أنبوب زجاجي بطول (1,8 م) مخصص للقياسات , عمودي التثبيت . عند جريان الماء إلى الأعلى فانه يفقد جزءا من ضغطه الاستاتيكي , عند ذلك يحصل الغليان التلقائي عند نقطة ما داخل الأنبوب الزجاجي تكون فيها درجة حرارة الماء مساوية لدرجة حرارة الإشباع في تلك النقطة .

تم قياس النسبة الوزنية للبخار (steam quality) في مخرج الأنبوب الزجاجي من خلال تجميع البخار المتولد في الأنبوب الزجاجي والمتكثف في جهاز التكثيف خلال فترة زمنية محددة .

لقد تم حقن فقاعات الهيدروجين في داخل المزيج الثنائي الطور أثناء جريانه في الأنبوب الزجاجي. حيث تعمل فقاعات الهيدروجين كمحفز لتوليد البخار . لقد وجد إن نسبة البخار الوزنية (steam quality) عند نهاية انبوبة الاختيار تزداد بنسبة (33 %) عما عليه بدون حقن تلك الفقاعات وذلك بتسليط فرق جهد قدره 12 فولت وتيار قيمته 7 أمبير, وانخفاض بنسبة (42%) من قيمة درجة الحرارة غير المتزنة عند نفس ظروف التأيين. إن تأثير عملية التائيين على نقطة بداية الغليان التلقائي ودرجة حرارته تم دراستها خلال الجزء العملي .

النتائج العملية تم مقارنتها مع النتائج النظرية والتي حصلنا عليها باستخدام موديل رياضي يستند في حله على معادلات الكتلة والزخم والطاقة لجريان ثنائي الطور مع فرض نمط جريان أنفصال عند الحل .

إن تأثير الطاقة الكهربائية المستخدمة في عملية التائيين يكون مبسطا في عمليات الحساب باستخدام معادلة توازن الكتلة والحرارة والتي تغطي الظروف المحيطة بالمنظومة .

KEYWORDS: Flash Evaporation, Electrolysis, Bubbles Injection, Steam Quality.

INTRODUCTION

Flow boiling is a boiling in a flowing stream of fluid, where the heating surface may be the channel wall confining the flow. The boiling flow is composed of a mixture of liquid and vapor. In this case individual dispersed bubbles are move independently up the vertical channel.

It is necessary to distinguish between boiling and flash evaporation. Boiling is a phase change accompanied by a supply of heat at constant pressure, while flashing is a phase change occurs due to reduction in pressure.

Boiling heat transfer is encountered in numerous engineering applications. One important field of application of boiling and evaporation is in desalination of sea water, which is becoming essential in some arid regions. That occurs by which the saline water is evaporated at reducing pressure. The vapor is taken to a condenser. The condensed steam is collected as fresh water; therefore, we need to enhance boiling.

There are several ways adopted for boiling enhancement. The main distinction is usually made between passive and active techniques. To augment boiling, passive techniques employ special boiling surface geometries, or fluid additive, such as roughening of the heat transfer surface, pitting the surface with corrosive chemical, integral fins or rolling, knurling integral finned tubes, coating the surface with a porous layer, etc. Active techniques need external power, such as electric or acoustic fields and surface vibration. The present research belongs to enhanced boiling by using electric field.

The process of water boiling enhancement using electric field is ensured by water ionization using electrical current. The ionization current breaks the bonds of water molecules casing generation of hydrogen and oxygen bubbles. These bubbles act as exciter for steam generation inside saturated water, (ZAGHOUDI, 2005).

The main target of the present research is to study the effect of saturated water electrolysis on the steam quality at the exit of vertically mounted test section and compare that with steam quality in the same test section without electrolysis.

W. NAKAYAMA, et a l, (1980) studied enhancement of nucleate boiling heat transfer with structure surfaces composed of internal cavities in the form of tunnels and small pores connecting the pool liquid and the tunnels. The authors dealt with porous surface which showed that wall superheat of a very small degree can start nucleate boiling. O. MIYATAKE , T.TOMIMURA, Y.ID, (1985) presented in their research an experimental study on the utilization of flash evaporation in power systems utilizing solar energy. They recognized that the spray flash evaporation were considerably faster than those of flowing liquid in conventional multistage flash evaporator and those of pool water exposed to sudden pressure drop in a container . They suggested that the best method of enhancement of flashing may be by injection of nucleation liquid through some nozzle configuration into a low- pressure vapor zone.

NOAM LIOR and ENJU NISHIYAMA, (1995) conducted experiments in a scale – down stage of flash evaporation at about (100 C°) to examine the effect of the generated hydrogen bubbles on flash evaporation. They have shown that electrically generated hydrogen bubbles have indeed promoted ebullition in flash stage regions where the superheat was otherwise too low for flash evaporation, and thus have increased evaporation rates resulting in reduction of up to (15%) in the non-equilibrium temperature difference.

AKRAM W. IZZAT, (2003) studied experimentally the flash evaporation of upward water flow in a (1.8 m) vertical mounted glass test section pipe. Multi-diameter test section (3cm-10cm) was used both as divergent and convergent channel. The author has been concluded qualitatively that the hydrogen bubble injection inside the two–phase mixture increases the steam quality in the test section exit.

G. HETSRONI, et al, (2004)**,** investigated experimentally saturated and sub-cooled pool boiling of environmentally acceptable surfactant solution on horizontal tube. The kinetic of boiling (bubble nucleation, growth and departure) were investigated by high–speed video recording.

In the present experiments water is allowed to flow vertically upward in a vertical cross sectional area channel. When it reaches a certain distance in the test section and when the local pressure becomes equal to saturation pressure corresponding to the local temperature, water starts to evaporate due to the flashing. The experiments are conducted using low water velocities in order to observe the motion of bubbles along the test section.

The local pressure, local temperature is measured at three longitudinally distributed positions along the test section. The water flow rate, boiler pressure are measured.

Water temperature is measured using calibrated thermocouples, thermistors and digital thermometer, while the static pressure is measured using the water manometer and the local pressure gage. The water flow rate is measured using calibrated flow meter.

The results of these measurements are compared with those obtained from the theoretical analysis. The theoretical analysis adopted in the present work is based on separated flow model.

EXPERIMENTAL APPROACH

The system arrangement shown in figure (1) is used to estimate the flow boiling enhancement by measuring the physical properties of the water during flashing process. The system consists of (1.8 m) length of the test section. The test section is manufactured from (PYREX) glass to ensure both clear visualization and good resistance to high temperature under maximum pressure of (1.2-1.6 bars). Test section diameter is constant (5cm).

Temperature and pressure measurement taps are distributed in the test section perimeter in three levels along the test section length. Four taps are specified for these measurements in each level. The first four taps are located at (15 cm) from the test section inlet. Each taps is a circular opening of (5 mm) inner diameter. The other four taps with the same inner diameter is located at (65 cm and 125 cm) distance from the test section inlet respectively.

These taps are specified for measurement purposes (static pressure and temperature measurements), also for the bubble air generation inside the test section during the ionization of water by the (electrolysis). The lower part of the test section is connected with the boiler, while the upper part is connected with enlarged glass test section part used for steam separation. This enlarged glass test section part is connected from its side to the horizontal glass pipe used to transport the water to the pump, while it is connected from the upper side to the condenser through flexible tube.

The water is circulated through the test section and the boiler using circulating pump located in perpendicular position to reduce the losses and any cavitation that could be anticipated during flash process. The boiler in the present experiments consists of electrically heated coil used to heat the water with heat capacity of (3kW). The body of the boiler is thermally insulated to reduce the heat losses to the environment .When the water passes through the boiler, its temperature rise above (100 C^0), as it is kept under the static pressure of the test section column (1.8m), then it enters the test section. The water velocity inside the test section is controlled by adjusting the water flow rate by the two valves (V1 and V2), while the water temperature during flashing is controlled by the cold water line valve (V5).

In order to ensure certain temperature difference between the boiler outlet and inlet , water flow rate inside the boiler is adjusted by mean of the same valves (V1 and V2) . The hot water circulation rate inside the test section is measured using flow meter (FM) of range (0.2-3 m^3/hr). In order to shorten the elapsed time required for the water to reach its steady state temperature, i.e constant temperature at test section inlet, the main parts of the experimental system are insulated with proper thermal insulation. Cold water at normal laboratory temperature (18 C^0) is added to the circulating water before the pump inlet by means of manually operated valve (V5) to balance the heat inside the system. For the purpose of mass balance, water is drained from the lower part of the test section by means of gravity action through valve (V4).

The fluid inside the test section is ionized by passing a (D.C) current across two electric poles at position (E1 and E2), see Fig. (1). The positive pole is fixed in position (1) ,while the negative pole is fixed in position (2) .The ionization current is measured at constant voltage by means of (12V – 10A) D.C power supply type (PC-10A) . These measurements are repeated at five different ionization currents, (3, 4.5, 5.5 and 7 A) using constant voltage power supply of (12V).

THEORITICAL ANALYSIS

The assumptions and the formulation of mass, momentum and energy equations shown below, described in details by (IZZAT, 2003).

Mass equation:

$$\frac{\partial M}{\partial z} = 0 \qquad (1)$$

Where:

$$M = \rho_f U_f As_f + \rho_g U_g As_g \qquad (2)$$

Momentum equation:

$$\rho_f U_f \frac{dU_f}{dz} = \frac{-dP}{dz} - \rho_f g Cos\theta + \frac{F_{fg} - Fw_f}{(1-\alpha)d\forall} - \frac{1}{2}\frac{1}{(1-\alpha)}(Ug - U_f)G\frac{dx}{dz} \qquad (3)$$

$$\rho_g U_g \frac{dUg}{dz} = \frac{-dP}{dz} - \rho_g g Cos\theta - \frac{F_{fg}}{\alpha d\forall} - \frac{1}{2\alpha}(U_g - U_f)G\frac{dx}{dz} \qquad (4)$$

Substitute for:

Cos θ = 1 since the flow in our case is in vertical direction pipe:

$$FW_f = \frac{fG_f^2}{2D\rho_f} = \frac{f\rho_f U_f^2(1-\alpha)}{2D} \qquad (5)$$

$$F_{fg} = \frac{12\pi\mu_f a(U_g - U_f)}{(1-\alpha)^2} \qquad (6)$$

$$\frac{dx}{dz} = \frac{\partial x}{\partial h}\frac{\partial h}{\partial z} + \frac{\partial x}{\partial p}\frac{\partial P}{\partial z} \qquad (7)$$

Energy equation:

$$\frac{\partial}{\partial t}\left[As\alpha\rho_g(e_g + \frac{U_g{}^2}{2}) + As(1-\alpha)\rho_f(e_f + \frac{U_f^2}{2})\right] +$$
$$\frac{\partial}{\partial z}\left[\alpha As\rho_g U_g(h_g + U_g{}^2) + As(1-\alpha)\rho_f U_f(h_f + U_f^2)\right] = \qquad (8)$$
$$(qe + qm - ws - w\tau)As - ((As\rho_g U_g + As\rho_f(1-\alpha)U_f)Cos\theta$$

After formulation of these equations the following final equations are used in the computer program to conduct the theoretical calculations:

$$\alpha = \frac{1}{1 + \frac{1-x}{x}\frac{\rho_g}{\rho_f}s} \qquad (9)$$

Where:

s: is the slip ratio between the phases $s = \frac{U_g}{U_f}$ (10)

$$\rho_f U_f \frac{dU_f}{dz} = \frac{-d\rho}{dz} - \rho_{fg} + \left(\frac{12\pi\mu_f a\left(U_g - U_f\right)}{(1-\alpha)^2 \frac{\pi D^2}{4} Dz} - \frac{f\rho_f U_f^2}{2D} \right) \frac{1}{(1-\alpha)} - \frac{1}{2}$$

$$\frac{1}{(1-\alpha)} (U_g - U_f)\left[\alpha\rho_g U_g + (1-\alpha)\rho_f U_f\right]\left[\frac{Cp(T_{i+1} - T_i)}{h_{fg}\Delta z} + \frac{\partial x}{\partial P}\frac{\partial P}{\partial z} \right] \tag{11}$$

$$\rho_g U_g \frac{dU_g}{dz} = \frac{-dP}{dz} - \rho_g\ g - \frac{1}{\alpha}\left[\frac{12\pi\mu_f a\left(U_g - U_f\right)}{(1-\alpha)^2 \frac{\pi D^2}{4}\Delta z} \right]$$

$$-\frac{1}{2\alpha}(U_g - U_f)\left[\alpha\rho_g U_g + (1-\alpha)\rho_f U_f\right] * \left[\frac{Cp(T_{i+1} - T_i)}{h_{fg}\Delta z} + \frac{\partial x}{\partial P}\frac{\partial P}{\partial z} \right] \tag{12}$$

Where:

$$T_{i+1} = \frac{T^*_{i+1} - \frac{x_i}{Cp_i} h_{fgi}}{(1 - x_i)} \tag{13}$$

$$T^*_{i+1} = \frac{\left[T_i \cdot \left(M_i\, Cp_i - \frac{hc_i Ac_i}{2} \right) + hc_i Ac_i Ta \right]}{\left(M_i Cp_i + \frac{Ac_i i\, hc_i}{2} \right)} \tag{14}$$

The first incremental value for the water temperature (Ti) at test section inlet is assumed to the initial value (T_0). The initial value is estimated using the following heat and balance equation:

$$T_0 = \begin{Bmatrix} QI + EP - hc*3.14*D*L*(Tout - Ta) + (Mi - Mout)*Cp*Tout \\ + Mc*Cp*Tc) \end{Bmatrix} /(Mi*Cp) \tag{15}$$

Where:

EP: is the electrolysis power.

$$EP = EV * EI \tag{16}$$

The mathematical calculations in this research take under consideration the mass and heat balance of the whole system which is realized by modifying the mathematical calculations performed by Akram.W.Izzat, using full theoretical equations based on postulated assumptions instead of incorporation of some measurement results in the computer program as input data.

Equation (16) simulates the effect of the electrolysis on the heat balance equation. This equation equals zero when the flow is without electrolysis after substitution the current input value equals to zero, while during electrolysis process steam quality is calculated based on different current values and constant ionization voltage.

RESULTS AND DISCUSSION

- Fig. (2) show steam quality at test section exit versus the ionization current used for hydrogen bubbles generation at water inlet temperature (101.2C^0). The figure clarifies the effects of the nuclei injection inside a saturated liquid on boiling enhancement. The curves plotted from the experimental and the theoretical results show that the steam quality in the exit of the test section increasing by increasing the amount of hydrogen nuclei generated inside the saturated water.

The effect of the non-equilibrium degree on the experimental results is clear when the saturated water flows in the test section without ionization. This makes a difference between the experimental and the theoretical results in such type of flow as shown in the figure. When water flows with electrolysis this difference becomes negligible as the electrolysis process eliminates the effect of the non-equilibrium on the experimental results. Accordingly the theoretical and the experimental results concur at certain ionization current.

- Fig. (3) show flash inception point versus the ionization current at water inlet temperature (101.2 C^0). The curves show that the flash inception point decreases by increasing the ionization current. The results obtained from the mathematical calculations coincide with those obtained from the measurements in the experiments without electrolysis while with electrolysis the experimental results show lower values than those obtained from theoretical due to the effect of hydrogen bubbles which initiates nucleate boiling earlier in the test section.

- Fig. (4) show water non-equilibrium degree, ^{0}C versus the ionization current at water inlet temperature (101.2 ^{0}C). From the curve it is clear that non – equilibrium degree decreases with increasing of the ionization current which in return decrease the distance of the flash inception point.

- Fig. (5-A&B) show the measured values of the local saturated water temperature and the saturation temperature based on local pressure versus test section length at constant mass flow rate and water inlet temperature. These figures show the position of the flash inception where the local water temperature equals to the saturation temperature. It is clear that this position is closer to the test section inlet when there is water electrolysis.

CONCLUSIONS

- The steam quality in the test section exit increases (33%) proportionally with the injection rate of the hydrogen nuclei by using water electrolysis in the saturation water as the non-equilibrium degree decreases (42%) by increasing this percentage.
- The flash inception point decreases as the ionization current increases at constant water inlet temperature and constant mass flow rate as the hydrogen bubbles acts as exciter for steam generation inside saturated water.
- The behavior of the saturated water during flashing process as moving upward in a constant cross -section channel is similar to that induced in a multi- diameter divergent and convergent channel investigated by IZZAT, A. W. (2003), which means that the channel shape has a slight effect on the process in low water velocity.

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NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
Cp	Water heat capacity	J/kg K^0
D	Diameter of the section	m
EI	Current of the electrolysis	A
EV	Voltage of the electrolysis	V
hc	Heat transfer coefficient between the test section wall and the surrounding	W/m^2 K^0
L	Test section length	m
M_i	Initial water mass flow rate	kg/s
M_e	Exit water mass flow rate	kg/s
QI	Heater power	W
Tc	Surrounding temperature	K^0
T_0	The initial value of the water temperature at test section inlet	K^0
Te	The water temperature at test section exit	K^0

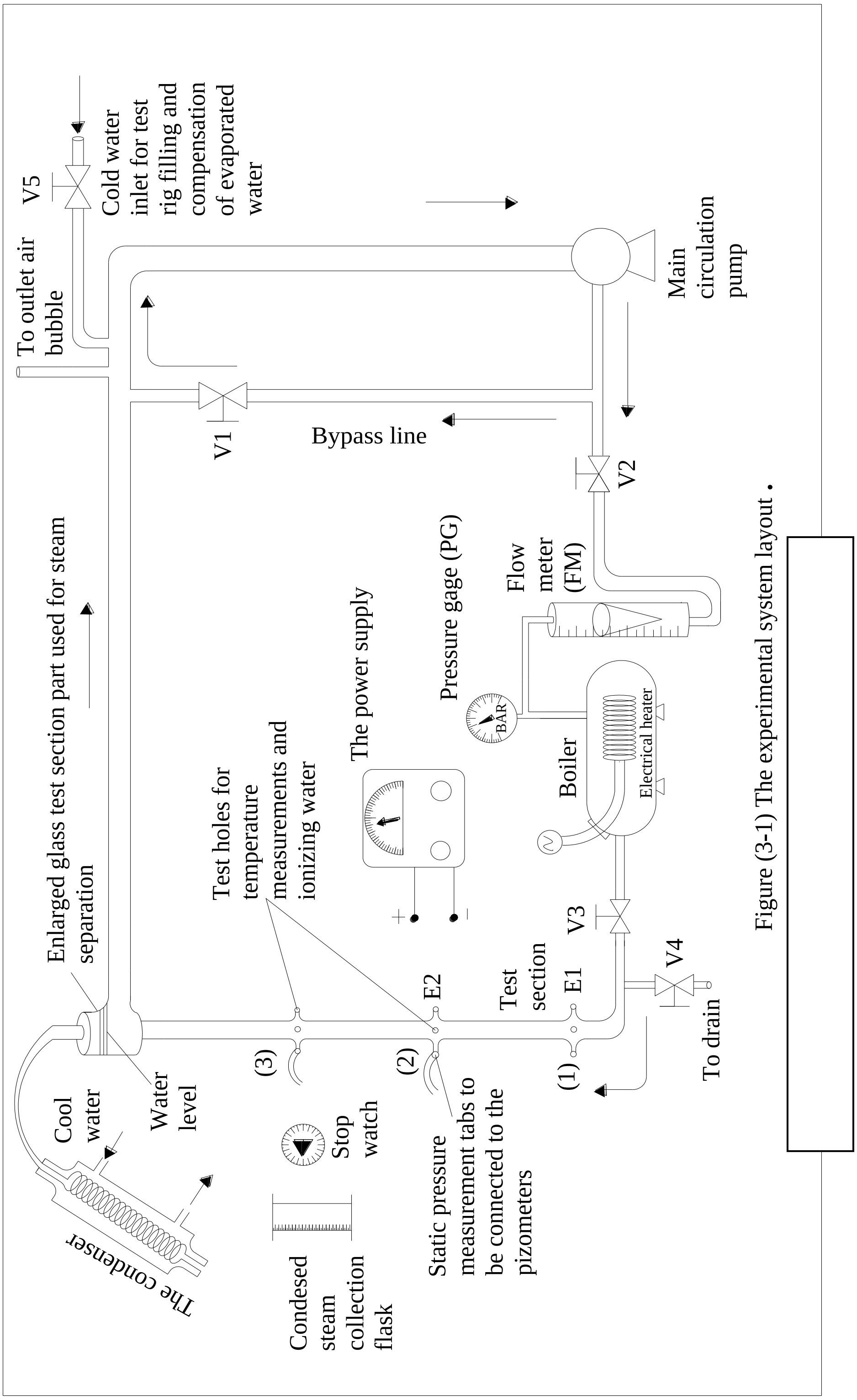

Fig. (1): The experimental system layout

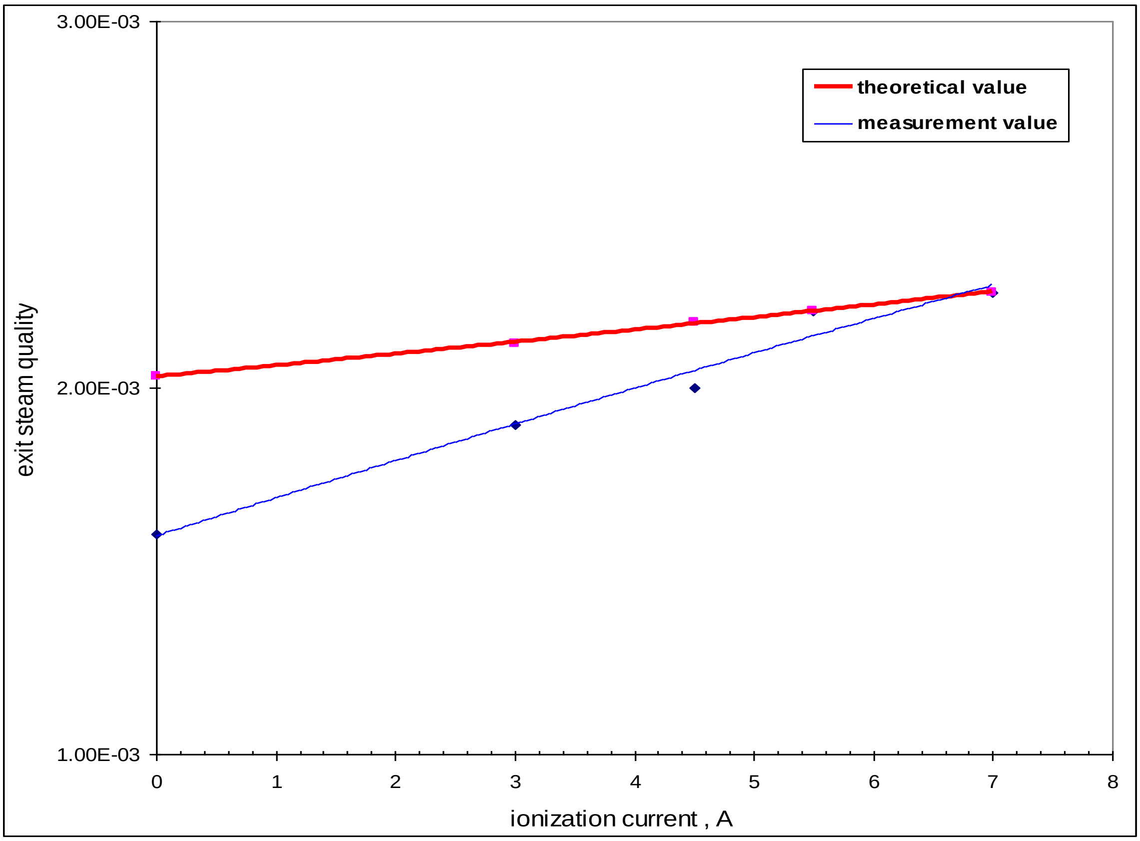

Fig. (2): Steam quality at test section exit versus the ionization current at T1=101.2 C. mass flow rate=0.1722 kg/s.

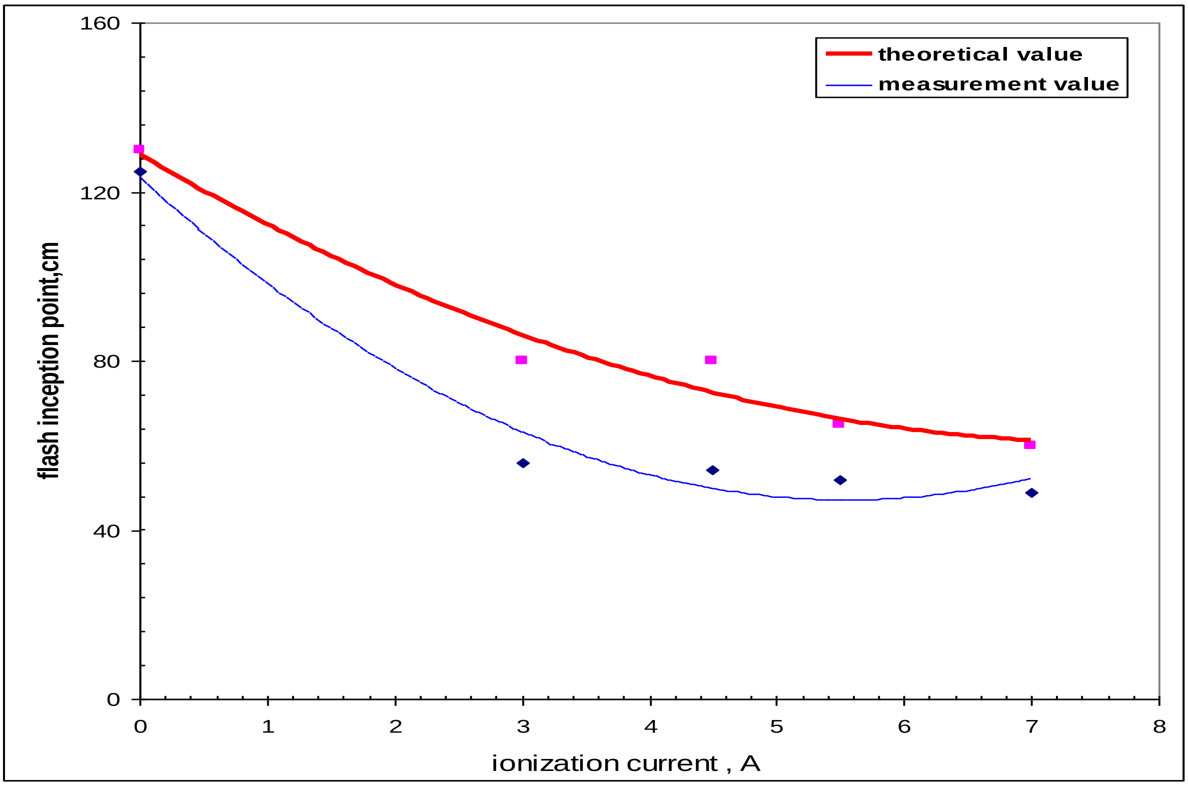

Fig. (3): Flash inception point versus the ionization current at T1 =101.2 C, mass flow rate =0.1722 kg /s.

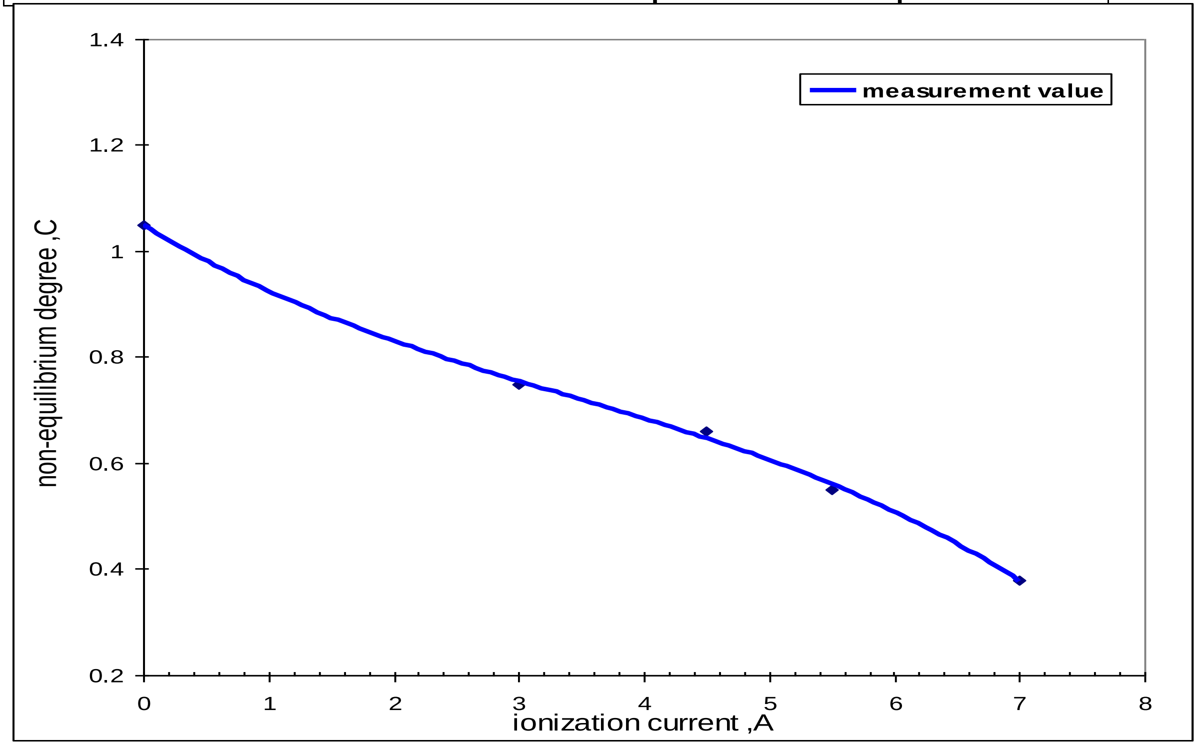

Fig. (4): Measured value of the non-equilibrium degree in the flash inception point versus the ionization current at T1=101.2 C.

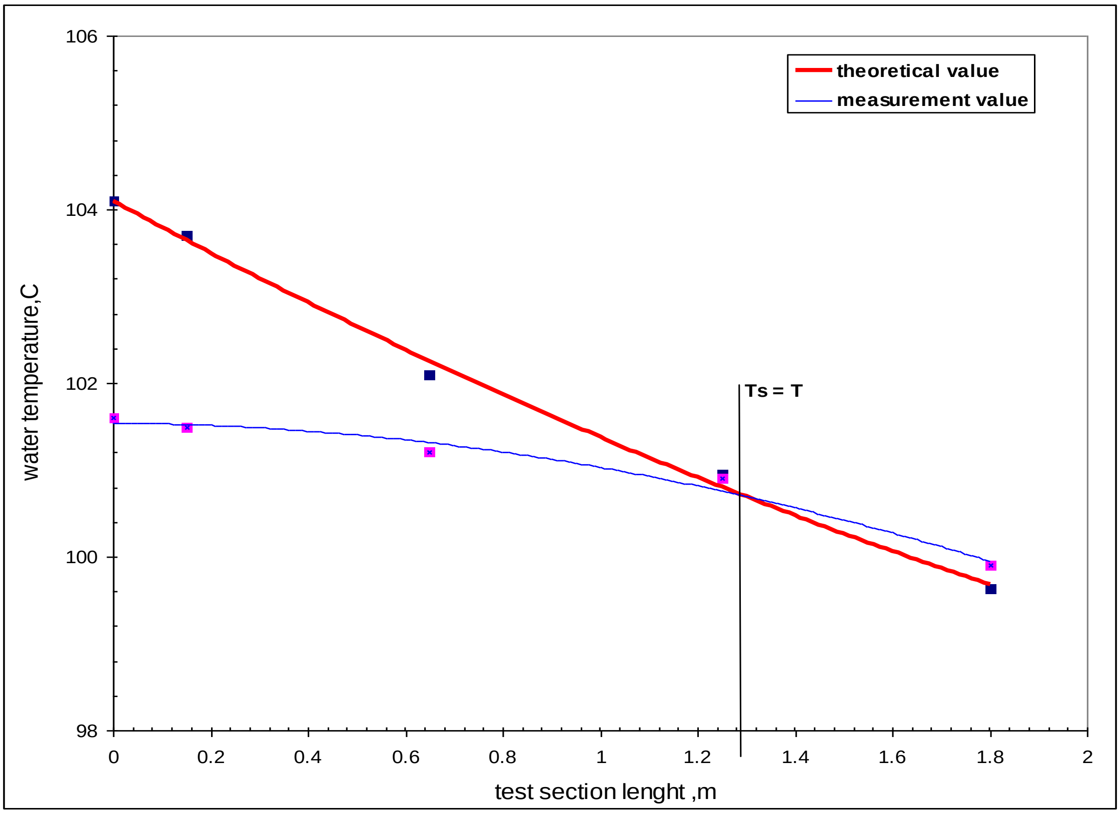

Fig. (5A): Experimental and theoretical saturation water temperature distribution along test section length at T1=101.2C, mass flow rate =0.1722 kg/s (without water electrolysis).

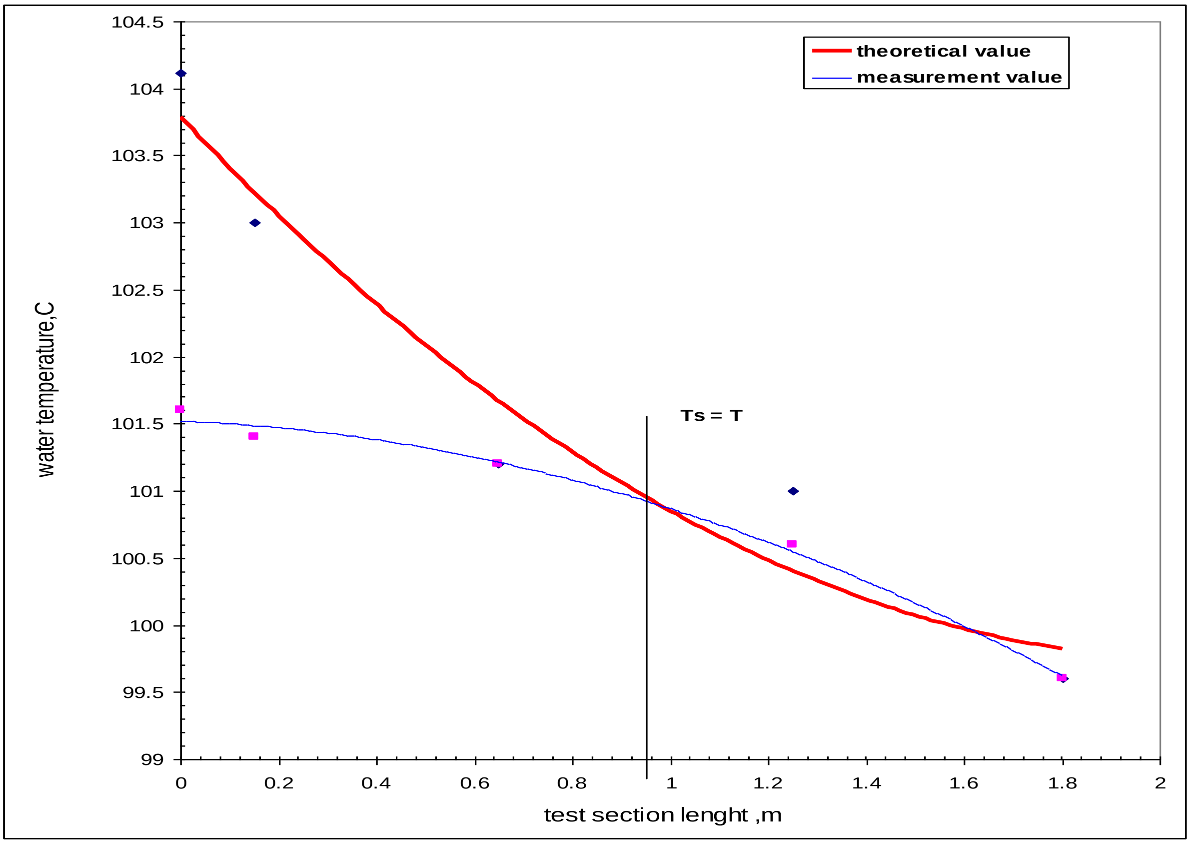

Fig. (5B): Experimental and theoretical saturation water temperature distribution along test section length at T1=101.2C, mass flow rate =0.1722 kg/s (with water electrolysis), current=3A.