Eng. & Tech. Journal, Vol. 30, No.11, 2012

Experimental Investigation of Water Vapor-Bubble Pump Characteristics and its Mathematical Model Reconstruction

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Received on: 19/9/2011& Accepted on: 1/3/2012

ABSTRACT

In this research, an experimental test has been conducted to study the pumping characteristics of a vapor-bubble pump based on water properties. It also includes a trial based on the obtained experimental data to correct and reconstruct the previously developed theoretical mathematical model of this bubble pump**.** The mathematical model that was developed for general fluid properties can be used after modification to represent the actual behavior of the water vapor-bubble pump. Most of the bubble pump configuration parameters which may affect its performance are experimentally investigated. Three different inner tube diameters (8, 10, 12 mm) with five submergence ratios (0.2, 0.3, 0.4, 0.5, and 0.6) are tested. The results showed that the bubble pump capacity increases with the thermal energy processed and continue to increase up to a maximum value then begin to decline. Each tube diameter has its own maximum discharge; the bigger tube diameter gives higher maximum discharge which is in turn increases with the increasing of submergence ratio. The experimental results of the pumping capacity are compared with those obtained from the mathematical model .Then the mathematical model is reconstructed by adding a correcting factor (K). This factor is necessary to account for the discrepancies that observed between the experimental and the theoretical results. The margin of error between the results of the resulting corrected mathematical model and the results of the practical test was acceptable and it can use this new model to analyze the performance of the bubble pump.

Keywords : Bubble pump Model reconstruction, Vapor bubble pump

تحقيق تجريبي لخصائص مضخة بخار الماء الفقاعية و أعادة بناء نموذجها الرياضي

الخلاصة

في هذا البحث، تم أجراء اختبار تجريبي لدراسة خصائص الضخ لمضخة البخار الفقاعية معتمدة على خواص الماء. ويتضمن أيضا محاكاة معتمدة على البيانات التجريبية لتصحيح وإعادة بناء النموذج الرياضي المطور سابقا لهذه المضخة الفقاعية. النموذج الرياضي الذي طور لخواص المائع العامة يمكن ان يستخدم بعد

https://doi.org/10.30684/etj.30.11.3
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التعديل لتمثيل السلوك الحقيقي لمضخة بخار الماء الفقاعية. اغلب عوامل الشكل الهندسي للمضخة الفقاعية والتي قد توثر على أدائها، قد تم تحقيقها تجريبيا. وقد تم اختبارا ثلاثة أنابيب بقطر داخلي (8، 10، 12 ملم) مع خمسة نسب غطس (0.2 ، 0.3 ،0.4 ، 0.5 و 0.6). أظهرت النتائج إن سعة المضخة الفقاعية تزداد مع زيادة الطاقة الحرارية المجهزة وتستمر بالزيادة لغاية قيمة عليا بعدها تبدأ بالانخفاض. إن لكل قطر سعته العليا وكلما كبر قطر الأنبوب زادت معه القيمة العليا لسعة الضخ والتي بدورها تزداد مع زيادة نسبة الغطس. تم مقارنة النتائج التجريبية لسعة الضخ مع نتائج النموذج الرياضي الذي تم أعادة بنائه بإضافة معامل التصحيح (K) . أن هذا العامل ضروري ليحسب مقدار الاختلافات التي ظهرت بين النتائج التجريبية والنظرية. إن نسبة الخطأ الناتجة بين نتائج الموديل الرياضي المصحح ونتائج الاختبار العملي كانت مقبولة وعليه يمكن استخدام هذا الموديل الجديد لتحليل أداء المضخة الفقاعية .

INTRODUCTION

A conventional absorption refrigeration system is running primary on heat energy, but requires mechanical energy to circulate the absorbent solution from the low pressure absorber to the high pressure generator. It is known that a bubble pump can be replace the solution pump for small capacities and driven only by heat.

A bubble pump is a fluid lift pump (i.e. Air or Vapor lift pump). It is a vertical tube Fig. 1, the fluid lifts up in the tube as a two-phase flow pattern. Heat supply or air injection to the fluid at the base of a vertical tube creates bubbles, thereby increasing the buoyancy of the fluid causing it to rise through the vertical tube. Hence, the important operating parameters of the bubble pump are tube diameter, length, submergence ratio, and heat input.

Literature on the two-phase flow provide more than sufficient information for the analysis of a bubble pump. It must also be mentioned that most of these publications refer to generally wide ranges of diameter and length used to lift the fluid in a dual and triple pressure absorption refrigeration systems.

M.A., Akeel [1], conducted a theoretical study to visualize the ability of operating a thermally operated water bubble pump that to be used in dual pressure LiBr-Water absorption refrigeration system for small cooling capacities. The results show that the tube length above 1.34 m has insignificant effect on the pumping capacity for all values of submergence ratio.

Stenning, A. and Martin,C. [2] introduced the basic principles of two-phase flow and momentum for investigation relatively small diameter air-lift pump. The airlift pump apparatus of this investigation was based on the practice of injecting air intermittently into a vertical riser tube at a location above a bottom opened end of the riser tube which is submerged in the liquid to be pumped. They observed that at a low air mass flow rate, the slug flow was dominant in the lift tube. By plotting the ∀L versus the ∀air for the various submergence ratios, it was found that there is an optimum air mass flow rate which produces a maximum water flow rate for a given tube diameter.

Delano [3], has addressed the design of a bubble pump for use in a single pressure absorption refrigeration cycle. The developed thermodynamic model was based on the air-lift pump analysis of reference **[2]**. It uses momentum balances and assigns a value to the slip ratio ($S=V_G/V_L$) between phase velocities, (In the slug flow regime, S values are 1.5 to 2.5) **Griffith, P. and Wallis, G**. **[4].** The model assumes laminar slug flow in the bubble pump with consideration of a single constant system pressure. The flow rate of the produced liquid first increases reaches a maximum value and then decreases with the increase in the heat input. In his study, he defines his vapor bubble pump to operate at the maximum water flow rate.

Sathe, A. [5] applied **Delano's** methodology [**3**] of the bubble pump. He concluded that a correction of lose factor (K) is necessary for the model to account for the discrepancies observed between the actual experimental observations and the assumption made in the theoretical analysis. The correction of lose factor established is a function of the vapor flow rate and the pump tube diameter as :

$$K = A\forall_g^4 + B\forall_g^3 + C\forall_g^2 + D\forall_g + E \qquad (1)$$

Where A, B, C, D and E are constants and are functions of the pump tube diameter, and $\forall$ volume flow rate. He found that the frequency of pumping action (fluid pulses out of the bubble pump per unit time) increases with increase of heat input and the mass flow rate of vapor increases linearly with the heat input where the mass flow rate of the produced liquid first increases, reaches a maximum value and then decreases with the increase in the heat input.

White, S.J.**[6]** performed experimental studies on an air-lift pump, which operates on the same principals as a vapor bubble pump, and the results were compared with five different bubble pump models. All of these models used basic conservation equations to formulate the average pressure gradient along the lift tube.

Pongsid S., Satha, A.[7] presented mathematical model to determine the maximum vapor-bubble pump performance. An individual test was conducted on a simple air-bubble pump apparatus of a given configuration (10.9 mm pump-tube inner diameter, 100 mm lift head and 65 cm driving head), at atmospheric pressure using water and air as working fluids. The obtained relation between liquid and air flows leaving the separator is :

$$\forall_{Liq} = -0.0004\forall_{Vap}^4 + 0.00625\forall_{Vap}^2 + 0.63772\forall_{Vap} - 0.46802 \qquad (2)$$

Where: $\forall$ is the volume flow rate.

The model was used to calculate the working fluid flow rate based on the heat input to study the performance of the experimental ammonia-water diffusion absorption refrigerator. The results showed that the absorption system performance is strongly dependent upon the bubble pump characteristics.

M.A., Akeel and et al.**[8]** presented mathematical model for vapor bubble pump used to simulate the thermal driving mechanism of the working mixture of Li-Br-water absorption refrigerator. It was proved that the slug flow provides the maximum liquid circulation rate. The most of the bubble pump configuration parameters which may affect its performance were investigated. Mathematical modeling of the bubble pump analysis had been generally developed and then it tested based on water properties. They obtained results was then correlated to express the maximum pumping capacity as a function of the bubble pump configuration. This correlation was limited for water properties only. They suggested that the submergence ratio of the bubble pump (H/L), which describes the average pressure gradient along the lift tube, can be expressed in terms of velocities, geometrical parameters, and fluid properties by using momentum and mass balances analysis which is;

$$\frac{H}{L} = \frac{V_1^{\,2} r_{w1}}{2\,gL\, r_{w,res}}\{2\frac{r_{w1}}{r_h} - 1\} + \frac{r_{TP}}{r_{w,res}}\{(\frac{4\,fL}{D})\frac{V_2^{\,2}}{2\,gL} + 1\} \tag{3}$$

Where; (H/L) : submergence ratio, V: velocity r : density, f friction factor.

Fig. 2, shows the results of above model representing the performance of the bubble pump 1.34 m long and 10 mm inner tube diameter and varying values of submergence ratios against different heat inputs. For any submergence ratio, the mass flow rate of liquid increases with increasing the amount of heat input because more vapor bubbles generated and hence higher buoyancy force. The liquid flow rate continues increasing up to its maximum value then it decreases, due to increase in the frictional pressure drop caused by higher velocity in the lift tube. Fig. 3, shows summarizing results for maximum pumping capacity against submergence ratio for three tube diameters.

The aim of the present experimental work of vapor bubble pump is to study and to obtain the actual relationship of water flow rates with varying heat input to validate the bubble pump mathematical model that is developed by **M.A., Akeel and et al [8]**. The valid model then can be applied to any other fluids or mixture.

EXPERIMENTAL SET UP

An open experimental bubble pump test rig based on water as the working fluid is designed, built and successfully operated. The experiments were performed in which the parameters affecting the bubble pump performance (tube diameters and submergence ratios), were changed. The schematic diagram of the experimental setup is shown in Fig.4. The main components of the setup are a receiver tank, heating element, the vertical vapor-lift tube, separator, connecting piping and fittings. Tubes of diameter 8, 10 and 12 mm, each of 1.34 m length [1], are tested to obtain the relationship between heat input at the generator (Q_P) and water flow rate (M_L) at different submergence ratio (H/L). Water level in the tank was varied based on the submergence depth needed. It is controlled using movable overflow pipe to maintain fixed water level during the operating process with continuous recirculation of the flooded water to the receiver. Heat is supplied to the bubble pump (lower end of the vertical tube) by 220 V, 2 kW electric heater that is connected via a single phase variable transformer 0–220 V to control the heater power supply manually. Additional electric heater is used for preheating the circulated water after the reservoir (before entering the bubble pump riser) to bring the water to the saturation temperature boiling point so that the supplied energy at the generator represent merely the latent of evaporation. Manual on-off power control is adopted to control the saturated temperature with continuous observation of the temperature level. Temperature is measured by a thermocouple (Chromel vs. Alumel) wire at three different points of the setup; T1, T2 and T3. T1 is located at the entrance of the bubble pump, T2 at the reservoir and T3 in the measuring cylinder. The prop ends of the thermocouple wires are located in the liquid water stream and are installed carefully without attachment to inner surface of copper tube. A scaled glass cylinder of 0.6 liters volume with stop watch is used to measure the amount of liquid water pumped by the bubble pump. The system is charged with pure water. The heating process at the generator created small vapor bubbles which merge into larger bubbles. The rising bubbles form slugs that occupy the whole cross-section of the glass tube and lift slugs of liquid water to the separating vessel. Heat losses are minimized by insulating the vertical pump riser, the generator, the separator, the reservoir and the pre-heater. Glass wool and asbestos insulation materials are used. The system is allowed to about two hours of operation to obtain the steady state which can be observed by the temperature values at points (T1, T2). Achieving the steady state, the measurements of energy input, water flow rate and the temperatures can be registered. The process of measurement of each fixed tube configuration is repeated three times to minimize the error of reading. Experimental data for the same tube diameter then can be obtained for other values of submergence ratios. Next, the tube diameter should be changed and tested following the same procedure mentioned above.

RESULTS AND DISCUSSION

The experimental behavior of the thermally operated vapor bubble pump is presented based on the pure water properties which correspond to (80 ^{0}C) in the receiver and saturated water (100 ^{0}C) at the entrance to bottom of the bubble pump. For the effect of geometrical configuration the following dimensions are tested (L =1.34m. inner tube diameters of 8, 10 ,12 mm , and H/L of 0.2, 0.3, 0.4, 0.5, 0.6).

Fig.(5) shows the performance of the bubble pump of 8 mm inner tube diameter with varying values of submergence ratios against different heat inputs. For any submergence ratio, the mass flow rate of liquid increases with increasing the amount of heat input because more vapor is generated and hence higher buoyancy force. The liquid flow rate continues increasing up to its maximum value then it decreases. The maximum value occurs at point where the increase in the frictional pressure drop caused by higher velocity in the lift tube exceeds the buoyancy effect of the vapor at that moment. Although the heat input increases, the pump can not exceed its maximum capacity. Further increasing the heat energy will generate more vapor and the produced high vapor velocity will change the flow pattern from slug to annular flow which causes the expected decrease in pumping capacity.

For the same tube diameter, increasing the submergence ratio leads to increase the liquid level(driving head) so the relative height to which the pump must lift the liquid decreases. So the flow rate can be increased by increasing the submergence ratio. Fig. 5, shows that for tube diameter of 8 mm., the discharge is increased from 0.195 kg/min at H/L=0.2 to 0.965 kg/min at H/L=0.6 .

It is known that larger tube diameter causes less frictional losses, so it adds an additional manner to improve the bubble pump performance by increasing the inner tube diameter see Figs. (6 and 7). In this case the amount of heat input should be also increased for maximum capacity which is more for larger tube diameter but still limited for its maximum quantity.

Figs (6 and 7) show the experimental results of bubble pump with tube diameter (10, 12 mm) it illustrate the same behavior of 8 mm tube diameter. Summarizing the above results for maximum discharge only, Fig.8 shows the variation in the maximum liquid flow rate against submergence ratio for the tested tube diameters.

One can conclude that the bubble pump of a given diameter has limited pumping capacity; each tube diameter has its own maximum discharge, the bigger tube diameter gives higher maximum discharge which is in turn increases with the increasing of submergence ratio. The optimum tube diameter is not limited but the submergence ratio cannot accede the value of 1.0, otherwise the liquid flows spontaneously because the driving head of the bubble pump will be higher than the lifting head. The optimum value of the thermal energy is associated with the location of the point processed, which represents the highest flow rate for each combination of the tube diameter and submergence ratio.

BUBBLE PUMP MODEL RECONSTRUCTION

Comparing the results that were obtained on the base of the theoretical model in previous study shown in Fig. 2 of tube diameter 10 mm, and 1.34m long **[8]** with that of the present experimental test Fig. 6 for tube diameter 10 mm, and 1.34m long, it is evident that the results exhibit the same typical qualitative behavior, with the m_L increasing sharply from minimum value at some minimum heat input then approaching a maximum value at higher heat input and then decreasing with further increase in Q_P . Comparing results on Fig. 3 of the bubble pump model **[8]** for maximum mass flow rate for three inner tube diameters with the present experimental test Fig. 8 for maximum mass flow rate for three inner tube diameters, it is clear that the theoretical results had a liquid flow rate higher than that obtained from the experimental test. The deviation between them for the maximum mass flow rate reaches 14.9% to 47.5% with tube diameter of 8 mm., 8.8% to 139.5% for tube diameter of 10 mm and 13.9% to 215%. for tube diameter of 12 mm. The expected reason for the deviation between the theoretical and experimental results is the friction parameter effect which is not considered exactly in the analysis, like the entrance and exit pressure losses and others which were neglected in the analytical model assumptions.

To modify the bubble pump analytical model for applicant calculations with any tube diameter and submergence ratio, a new run for the model is performed based on the theoretical model taking an approximate trial values for a loss factor parameter say "K" which is replaced here instead of the term ($4fL/d$) of eq. (3) such that the reconstructed model becomes as ;

$$\frac{H}{L}=\frac{V_1^2 r_{w1}}{2gLr_{w,res}}\{2\frac{r_{w1}}{r_h}-1\}+\frac{r_{TP}}{r_{w,res}}\{K\frac{V_2^2}{2gL}+1\} \quad (4)$$

The appropriate K value for each run should be such that the obtained value of the maximum liquid flow rate based on the corrected model matches that value obtained from the experimental test at the same operating conditions. This run is repeated for three tube diameters and five values of submergence ratios for each diameter.

The obtained 15 K's values are shown in table (1) and are correlated using least-square method with the aid of Microsoft Office Excel 2003 to find K's value as a function of tube diameter (d) and submergence ratio (H/L), as in eq. (5).

Table 1 Corrected K's values for different tube diameters and submergence ratios

H/L	d=8 mm	10 mm	12 mm
0.2	10.4014	7.017	2.8046
0.3	8.6252	7.431	5.4088
0.4	6.849	7.854	8.013
0.5	5.0728	8.259	10.6172
0.6	3.2966	6.603	13.2214

$$K=[10951(H/L)-4089.4]d+(-105.37(H/L)+46.669) \quad (5)$$

Where;
d : bubble pump tube diameter,
H/L: submergence ratio.

This K value (The correlated equation), then can be inserted in eq. 4, for any bubble pump tube diameter within the tested range used in the present work and different submergence ratios. To check for the new corrected model, Figs. (9 to 11) are plotted to show the extent of matching between the corrected model results and the experiment data and compare them with the results of the non corrected model. The maximum error percent for the maximum mass flow rate obtained from the corrected model compared with that of the experimental data are about (+14.66 % and -9.4%) for tube diameter (8 mm) Fig.(9), (+6.22% and -10.37 %). for tube diameter of (10 mm) Fig.(10), and (+7.491 %) for tube diameter of (12 mm) Fig.(11). The percent errors are acceptable and the corrected model then can be used to analyze the bubble pump behavior.

CONCLUSIONS

The following conclusions are drawn from the discussed results;

1- The experimental test of the vapor bubble pump has been successfully conducted to illustrate the pump behavior. This behavior showed the same trend as that obtained from the previously done theoretical bubble pump model of [8].

2- The pumping capacity is affected positively with the increasing of both the tube diameter and submergence ratio. The optimum tube diameter is not limited but the submergence ratio cannot accede the higher value of 1.0.

3- The optimum value of the supplied thermal energy associated with the location of the point processed, which represents the highest flow rate for each combination of the tube diameter and submergence ratio.

4- The previously developed bubble pump model of [8] has been reconstructed and gives a good approximation for maximum discharge which matches the experimental results within 14.66 to -9.4 % percent errors depending on the tube configuration.

RECOMMENDATIONS

It is recommended that further work should be done to study experimentally the applicability of the reconstructed model on other fluids rather than water.

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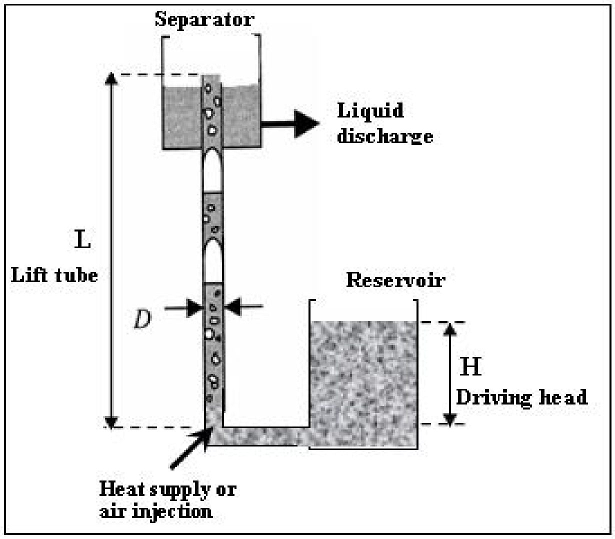

Figure (1) Bubble pump configuration

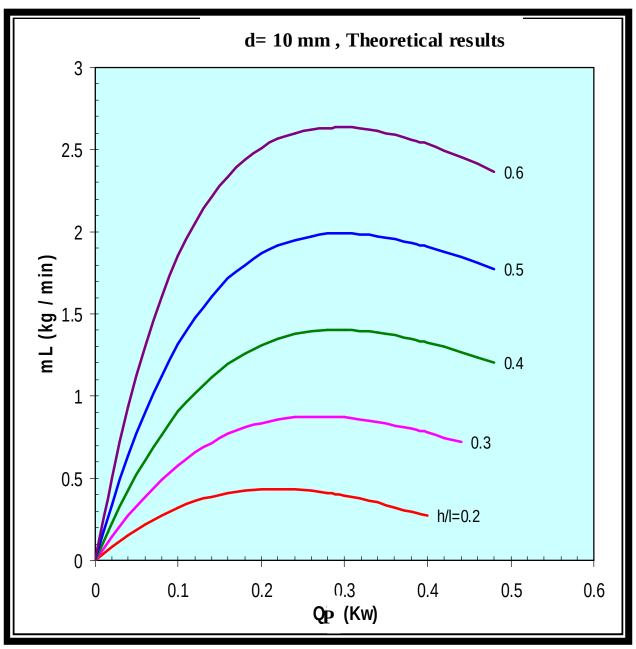

Figure (2) Bubble pump capacity (mL) vs. heat input for inner diameter 10 mm, L=1.34m at

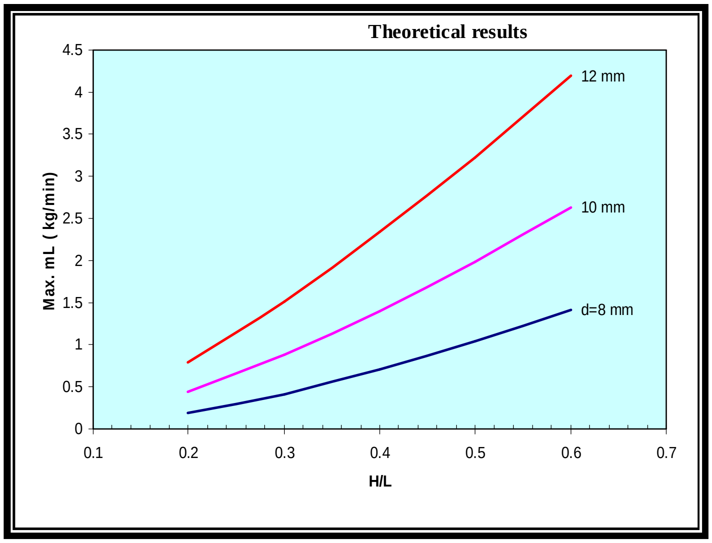

Figure (3) the maximum bubble pump capacity at different submergence ratios and tube diameters

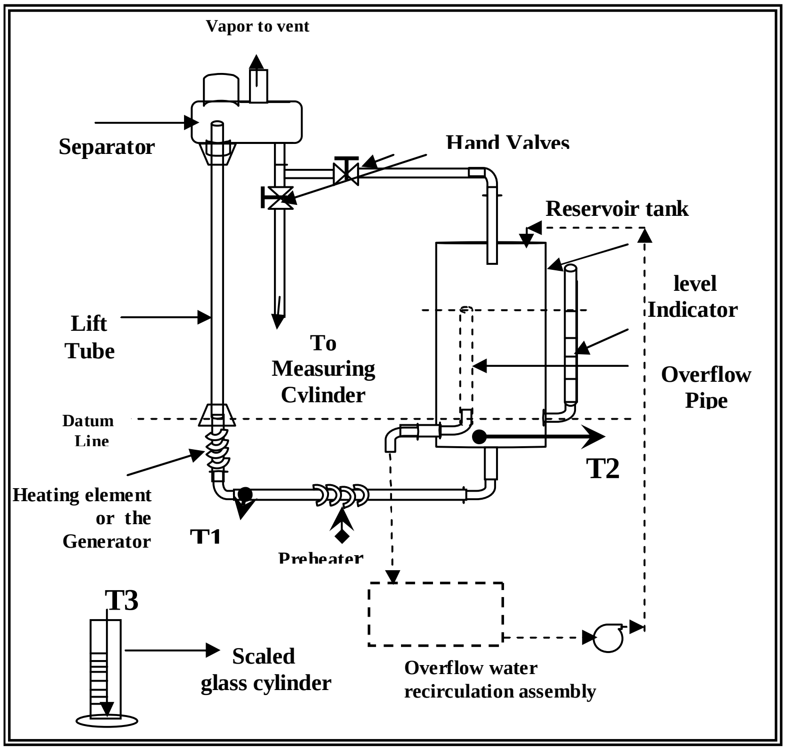

Figure (4) The schematic diagram of bubble pump test rig

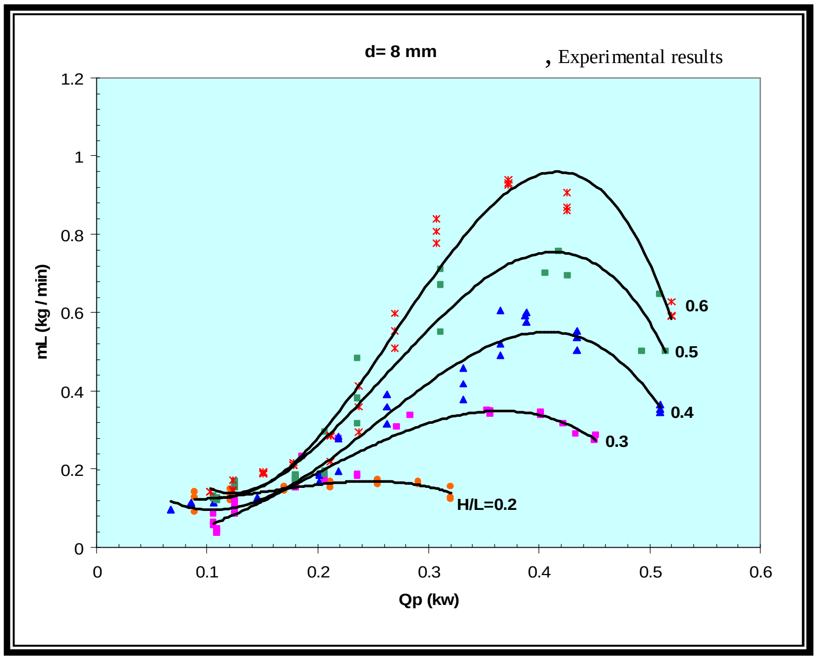

Figure (5) the experimental measurements of water flow rate vs. heat input of tube diameter 8 mm, length 1.34m.

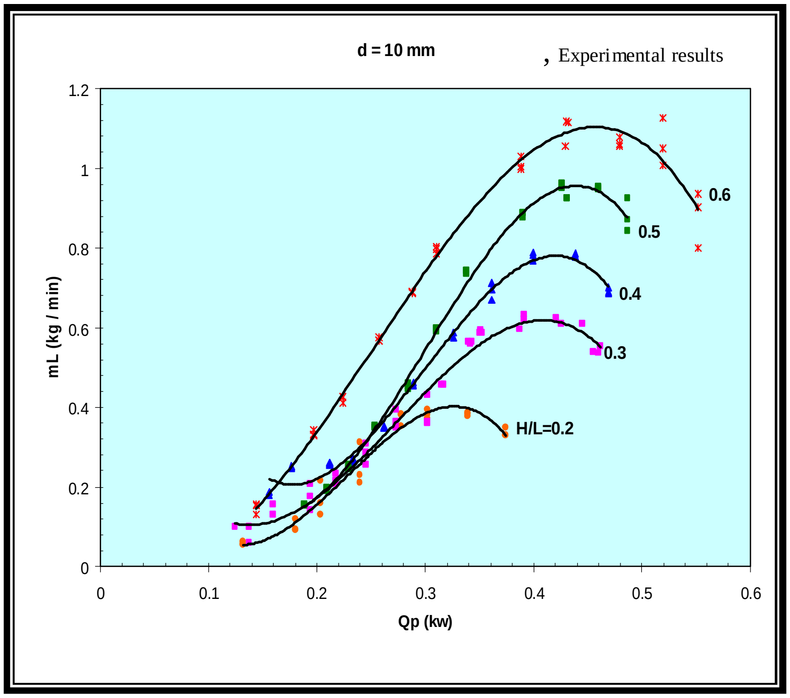

Figure (6) the experimental measurements of water flow rate vs. heat input of tube diameter 10 mm, length 1.34m.

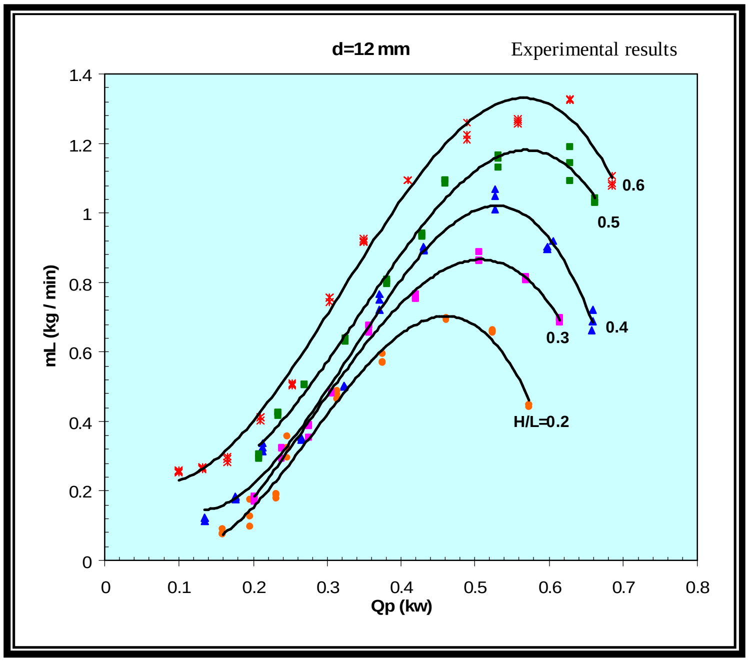

Figure (7) the experimental measurements of water flow rate vs. heat input of tube diameter 12 mm, length 1.34m.

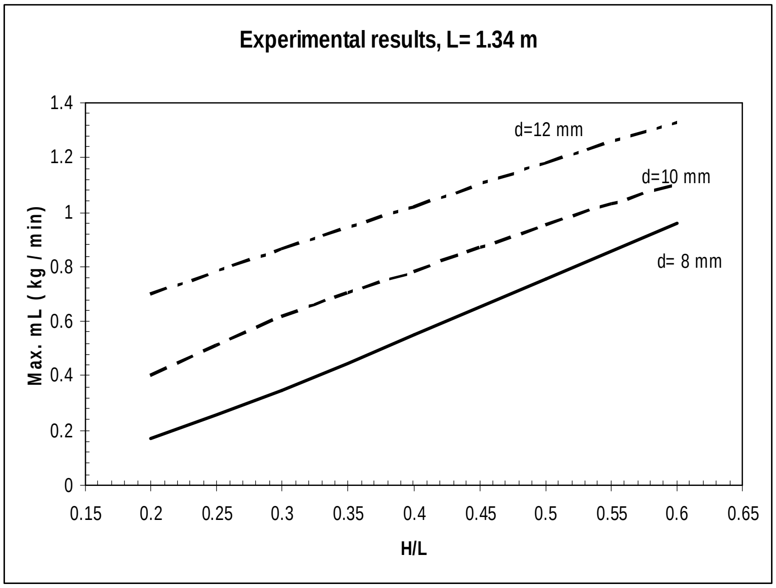

Figure (8) the maximum bubble pump capacity at different submergence ratios and tube diameters of experimental work

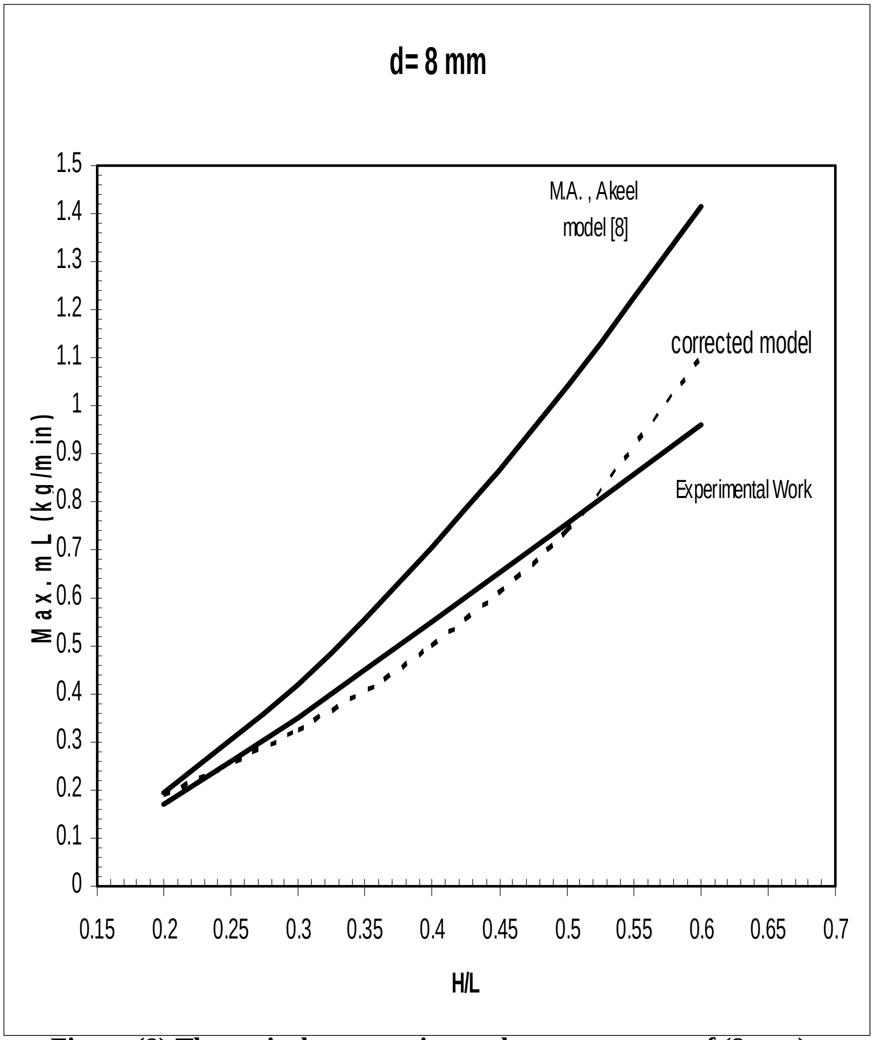

Figure (9) Theoretical vs. experimental measurements of (8 mm) inner diameter and tube length (1.34 m), with variation in submergence ratios.

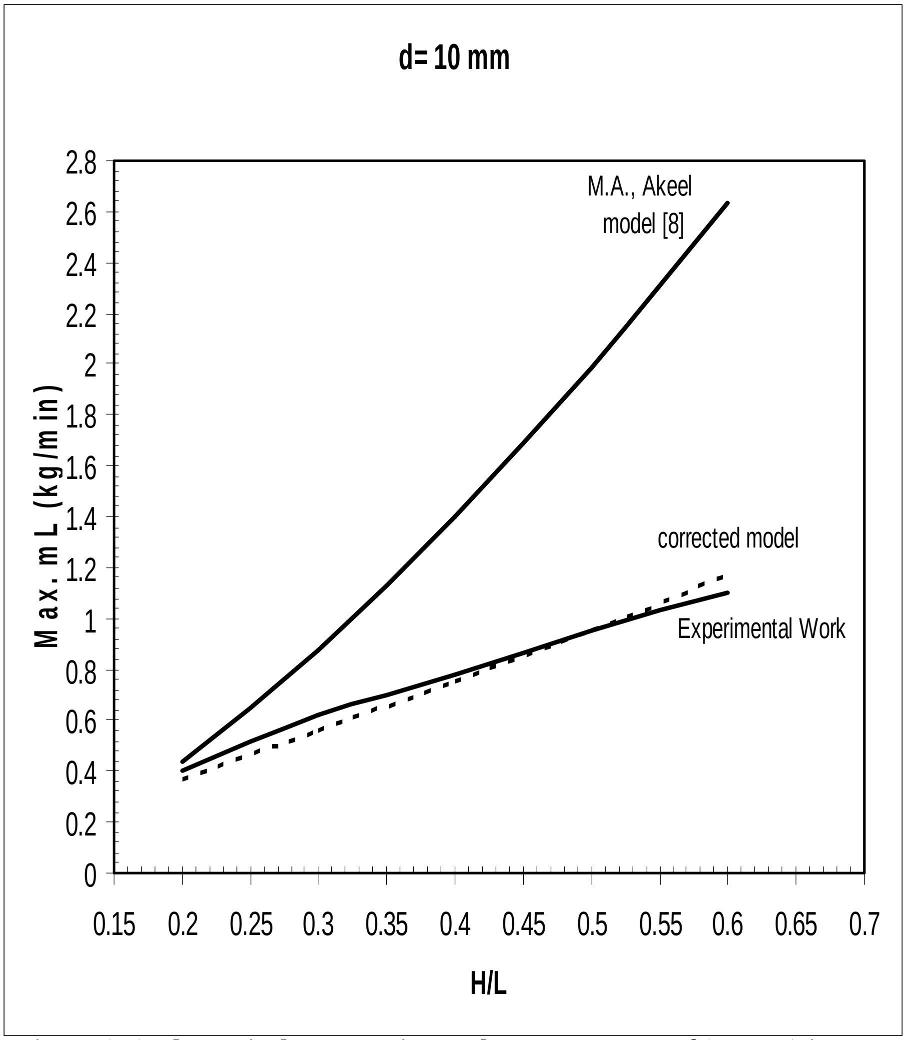

Figure (10) Theoretical vs. experimental measurements of (10 mm) inner diameter and tube length (1.34 m) , with variation in submergence ratios.

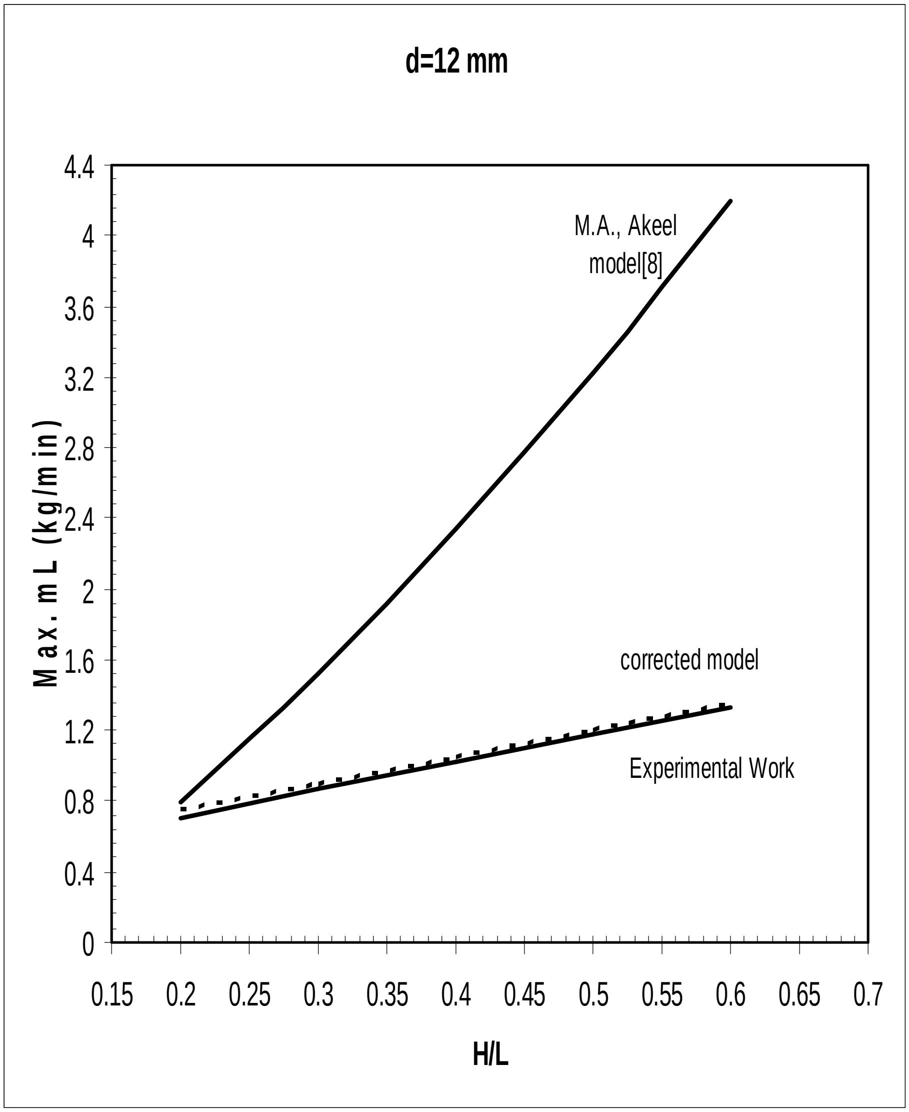

Figure (11) Theoretical vs. experimental measurements of (12 mm) inner diameter and tube length (1.34 m) , with variation in submergence ratios

NOMENCLATURE

Symbols	***Definition***	***Units***
A	Cross- section area of bubble pump tube	m^2
d	Bubble pump tube diameter	m
f	Friction factor	-
g	Gravitational acceleration	m/s^2
H	Height of liquid in the reservoir	m
K	Loss factor	-
L	Bubble pump tube length	m
$\dot{m}$	Mass flow rate	kg/s
J	Superficial velocity	m/sec
Re	Reynolds number	-
S	Slip ratio	-
mL	Liquid mass flow rate (used in Fig.)	$kg/\min$
V	Velocity	m/s

GREEK SYMBOLS

Symbols	***Definition***	***Units***
r	Density	kg/m^3
$\forall$	Volume flow rate	m^3/s

SUBSCRIPTS

Symbols	***Definition***	***Units***
1, 2,	State points	-
w, res	Water, reservoir	-
h	Homogeneous condition	-
g	Gas	-
L	Liquid	-
TP	Two-phase	-
v	Vapor	-