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Effect of air injection method on the performance of an air lift pump

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Abstract

Air lift pump performance was investigated experimentally for different submergence ratios (the ratio between the immersed length of the riser and its total length) using different air injection footpiece designs. For this purpose an air lift pump with a riser 200 cm long and 2.54 cm in diameter, was designed and tested. Nine different air injection footpiece designs were used at four submergence ratios with different air injection pressures (from 0.2 to 0.4 bar). An area of 10 mm^2 was chosen and divided into nine injection hole arrangements (1, 2, 3, 4, 6, 15, 25, 34 and 48 holes) to cover the whole experimental range. Four submergence ratios were used for this work: 0.75, 0.7, 0.6 and 0.5. The experimental results showed a marked effect on the pump performance when operated with different types of injectors at different submergence ratios. The results indicated that the disk with three holes (D3) gives the highest efficiency at nearly all submergence ratios. Moreover, it is found that there is a suitable disk design for maximum water flow rate at every submergence ratio. Further, the highest efficiency resulted at the largest used submergence ratio, namely 0.75. The pump capacity and efficiency were found to be functions of air flow rate, lift ratio, and injection pressure. © 1999 Elsevier Science Inc. All rights reserved.

Keywords: Air lift pump; Submergence ratio; Air injector

1. Introduction

An air lift pump is a means of artificially lifting a liquid. The air lifting operation depends on the injection of air or gas at the bottom (or near to the bottom) of a pipe partially submerged in the liquid to be lifted. In general, gas lift pumps have the advantages of not having any moving parts, and thus no lubrication or wear problems. So, theoretically, the maintenance of this kind of pumps has a lower cost and a higher reliability in some applications, such as raising a liquid with solid parts (e.g., sludges and slurries). Air lift pumps are, however, usually used for difficult pumping operations, such as underwater explorations or to raise coarse particle suspensions in the dredging of river estuaries and harbours, the mining of minerals from ocean beds and the recovery of coal in mine shafts. The great advantage in utilization of an air lift pump is that it can be used to pump fluids which are corrosive for metals, explosive, toxic, volatile or evaporative. Recently, air lift pumps have been used for pumping boiling liquids where there is a change in phase from liquid to gas. In petroleum fields gas lift pumps are used for raising oil form weak wells. They also have a wide range of applications in chemical and nuclear areas.

In spite of the simple construction and operation of this pump, its theoretical description is not simple. The performance of an air lift pump has early been predicted by using energy balance and empirical correlation methods. The energy balance method considered the losses as a factor in evaluating the overall efficiency, which is not accurate. The empirical correlations are not valid for a very wide range of operating conditions and also for high lifts. During the last 30 years, the air lift pump was also analyzed in terms of the theory of two-phase flow.

Many studies investigated the effect of the pump variables (riser diameter, submergence ratio, design of footpiece) on the pump performance. Stepanoff (1929) used thermodynamics theory. He proposed parameters affecting the pump performance, such as submergence ratio and riser diameter. Nicklin (1963) presented a theoretical treatment of air lift pumps, based on the theory of two-phase flow, to give the optimum conditions for pumping water in round pipes. Todoroki et al. (1973) used a suitable correlation for gas holdup and void fraction to determine the friction losses. They obtained a good agreement with the experimental data in the range 25 mm $< D <$ 100 mm and for submergence ratios of 0.4–0.8. Hjalmrs (1973) studied the critical lift and the time of oscillation in case of instability of air lift pumps. The theoretically computed values of the critical rise and time period of oscillation were shown to be in a satisfactory agreement with observations. Kato et al. (1975) investigated the performance of low head air lift pumps used to lift particles. The use of the momentum equation of the flow coupled with the equation of motion of a single solid particle gives a good agreement with the experimental results.

Sharma and Sachdeva (1976) showed which factors affect the performance of large diameters air lift pumps operating in shallow water. They found that when the air rate increases the slugs of water and air transform themselves into an annular

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flow. Moreover, the increase of the air flow rate causes an increase in the water flow rate, up to the condition of maximum flow. A further increase in the air flow rate causes a tendency towards decrease of the water flow rate. The decrease of the submergence ratio causes a reduction in the water flow rate and pump efficiency.

Khalil and Elshorbagy (1979) designed a new air lift riser to reduce the friction between the mixture and the riser internal surface, in order to increase the riser pumping efficiency. The experiments showed a reduction in the flow friction coefficient for both single- and two-phase flows. By using this type of pump the riser efficiency increased and the static submergence required to start the flow was reduced. Jeelani et al. (1979) tested the validity of the theoretical model proposed by Hussain and Spedding (1976) for small diameter air lift risers. The model was valid for low diameter air lifts (less than 3.5 mm). The low slip and hence the high efficiency of smaller diameter air lifts make them useful in special applications. Further, Parker (1980) studied the effect of the footpiece design on the performance of air lift pumps. For this purpose he investigated experimentally two types of injectors (nozzle air footpiece injection and air jacket injection). He found greater pumping capability at high air flow rates with small orifice area but the efficiency was very low. He extended the model of Stenning and Martin (1968) taking into account the momentum of the air injected in the nozzle footpiece. Halde and Svensson (1981) designed an air lift pump for continuous sand filters. They found good agreement between the experimental results and the design data. They presented a chart for the optimum size for many conditions of continuous sand filter air lift pumps. Sekoguchi et al. (1981) investigated experimentally the pumping characteristics of an air lift system consisting of an air/water separator and a constant head tank. Noting the feed water, they observed that the flow rate fluctuates markedly in the whole range of their experiment.

Sorour (1984) carried out an experimental investigation on the transition from bubbly to slug flow in a vertical annulus. He showed that the parameters which affect the transition from bubbly to slug flow are void fraction, disk hole number and bubble size. Apazidis (1985) studied the stability conditions of an air lift pump. He found that when the bubble diameter was reduced from 4 to 1 mm the water flow increases under the same conditions, for low flow rates. At higher flow rates the difference in slip ratio decreases and the friction effects become dominating, which results in approximately equal values of the lift for flows with different bubble sizes. Sorour and Elbeshbeeshi (1986) carried out investigations of the hydrodynamic characteristics of bubbly flow in a vertical annular channel. They obtained parameters affecting the void fraction and pressure fluctuations in vertical annular channels.

Clark and Dabolt (1986) introduced a general design equation for air lift pumps operating in the slug flow regime. Their operating curves agree with the curves given by the design equation. Morrison et al. (1987) showed the effect of using four and eight diffuser ports as a method of injection on the performance of air lift pumps. The experimental data showed that the eight-port diffuser is more efficient than the four-port one. The data indicated that the efficiency was greatly affected by the air flow rate and injection method. Ansari and Sylvester (1988) developed a model for two-phase bubble flow in vertical pipes based on the assumption that the flow is fully developed and stable. Reinemann et al. (1990) studied the effects of tube diameter on the performance of air lift pumps. They found that the liquid slugs have a turbulent velocity profile for Reynolds numbers less than 500. Further an erratic behavior of a very small gas bubble suspended in liquid slugs, was shown. Agreement between theory and experiment was found to exist, except when the gas flow rate is low and the submergence ratio less than 0.7.

Khalil and Mansour (1990) carried out experimental studies of the effect of introducing a surfactant in the pumped liquid. They proved that the use of a surfactant in small concentrations always increases the capacity and the efficiency of the pump. Further, they found that the pump performance is a function of the air volumetric flow rate, lift ratio, supply pressure and the surfactant concentration. Mansour and Khalil (1990) also carried out experimental tests to study the effect of the injection method on the air lift pump performance.

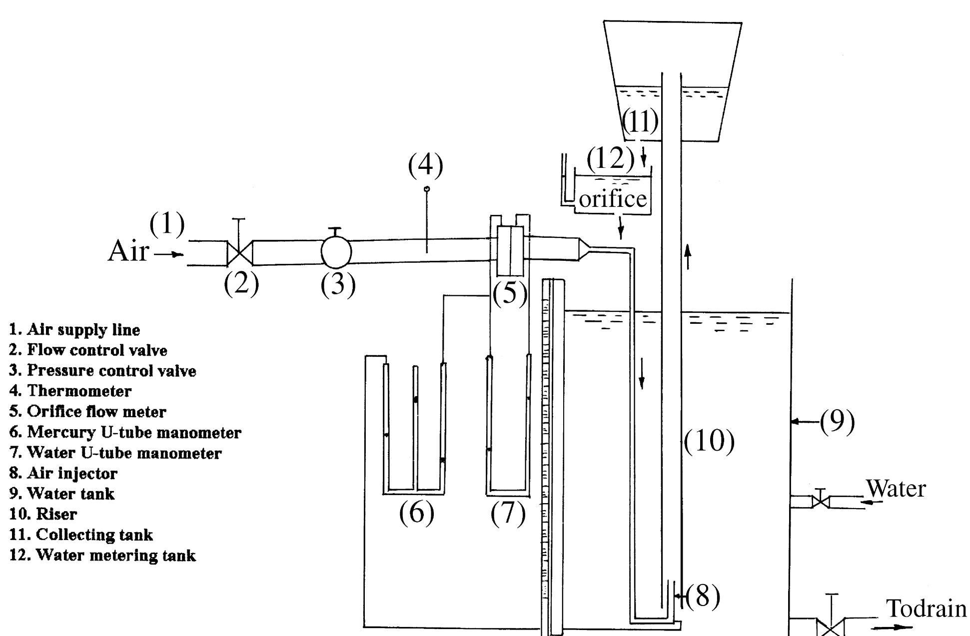

Fig. 1. A schematic diagram of the air lift pump set-up.

Their results showed that the initial bubble size and bubble distribution in the main lift riser have great influence on the pump performance, where good homogenous mixtures formed in the riser reduce slip and consequently increase the air lift pump efficiency.

The main objective of the present work is to study experimentally the effect of nozzle footpiece design on air lift pump performance. In addition comparisons between experimental and theoretical results are also presented.

2. Experimental setup

The experimental apparatus shown in Fig. 1 is constructed and made available for evaluating the pump performance. It consists of a vertical tube as a riser fixed in a water suction system reservoir and measuring instrumentation equipment. Measurements were performed of the injected air flow rate, air supply and injection pressures, pumped water discharge and submergence level of the riser in the suction water tank.

The pump riser is a vertical commercial steel tube of internal diameter 25.4 mm and outside diameter 33 mm. The total length of the riser is 2 m. It is fixed vertically in the middle of a cylindrical suction water reservoir 0.6 m in diameter and 1.8 m high with its foot end 0.2 m above the bottom. The suction reservoir is equipped with a water level indicator made of a vertical glass tube and scale. The absolute roughness of the internal surface of the riser tube was measured using a roughness meter and was found to be 0.15 mm. The foot end surface of the riser is made flat using lathe cutting at right angles to the tube axis. Burrs are removed and the edge is not rounded.

Table 1
Specifications of injection discs

Plate no.	Number of holes	Hole diameter (mm)	Total area of holes (mm^2)
D1	1	3.5	9.62
D2	2	2.5	9.82
D3	3	2.1	10.39
D4	4	1.7	9.08
D5	6	1.5	10.6
D6	15	0.9	9.54
D7	25	0.7	9.62
D8	34	0.6	9.61
D9	48	0.5	9.42

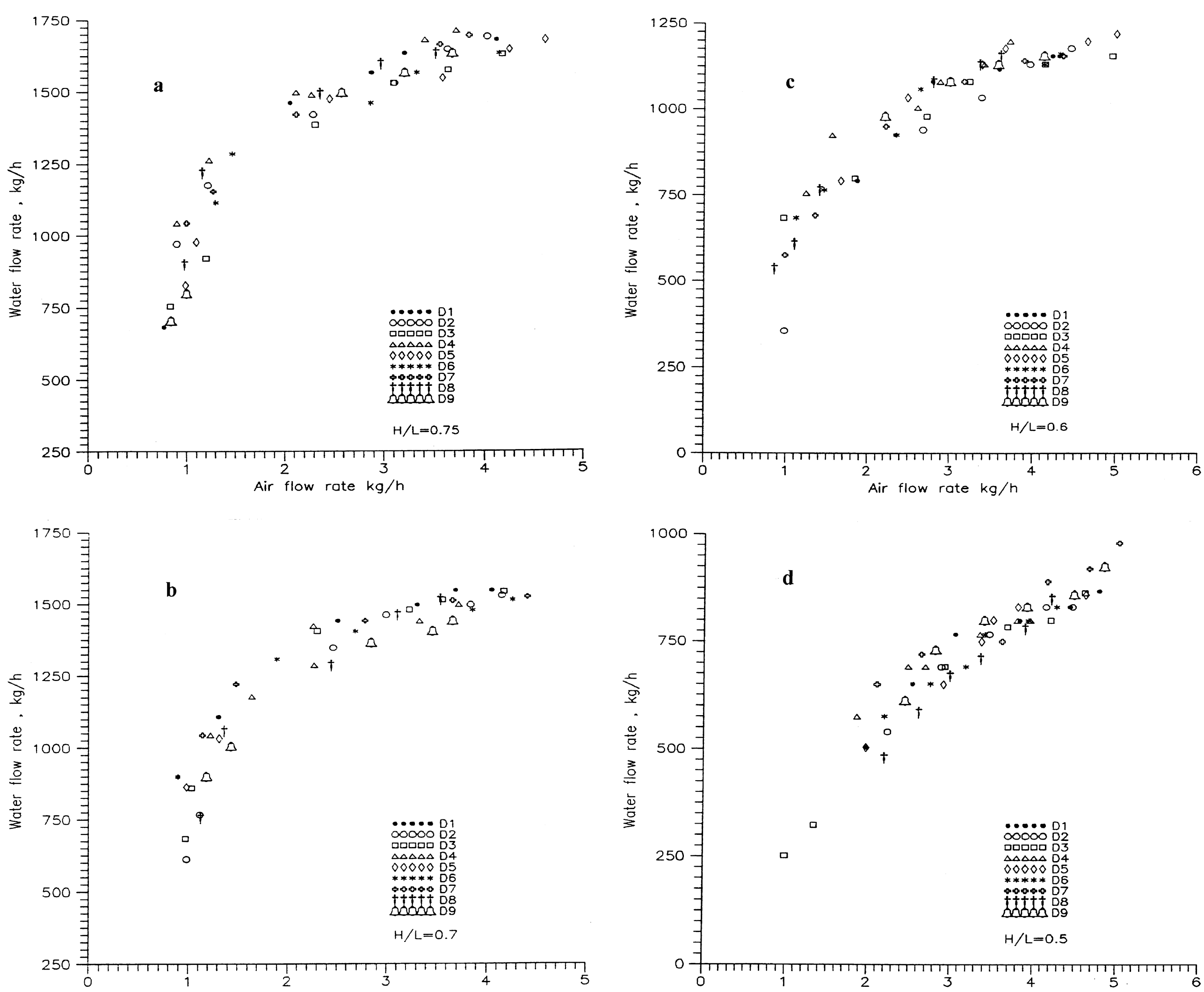

Fig. 2. Variations of air flow rate versus water flow rate for different injection disks and submergence ratios.

The upper end of the riser pipe is connected to an overhead water collection tank, where air is removed from the pumped mixture, and water flows from this tank to a smaller metering tank.

Air is supplied to the air injection system from a central air compression station. The station consists of a 55 kW Ingersoll Rand screw compressor delivering 8.2 m^3 free air per min at a pressure of 8 bar, a mass refrigeration dryer and filtration system, and an air reservoir of 3 m^3 capacity. Air goes from the air reservoir through a 25 mm diameter pipe line to a on/off valve, then to a pressure reducing valve (regulator), where the pressure is reduced to the working pressure (0.2–0.4 bar). The air then goes through an orifice meter equipped with a 5.1 mm diameter sharp-edged orifice in a 25.4 mm PVC pipe. Air is metered and the mass flow rate is determined from readings of the upstream pressure and the temperature together with the reading of the differential pressure across the orifice.

Differential pressure is measured using a water U-tube manometer and the upstream pressure is obtained using a mercury U-tube manometer. A mercury in-glass thermometer is used for measuring the upstream air temperature. The air then proceeds from the orifice meter through a 13 mm diameter tube to the air injector, that is fixed at a distance of 20 cm from the pump riser foot end. The air injector is simply constructed from an air distributing plate clamped to the injection pipe. It controls the shape and volume of air bubbles. The air distributing plate is a disk in which holes with different shapes and numbers are drilled. Nine discs are used with different hole sizes and numbers to provide a fixed cross-sectional area, nominally 10 mm^2, to cover the intended experimental range. The discs were all 12.5 mm in diameter, cut off an aluminum sheet of 1 mm thickness. Specifications of the used discs are shown in Table 1.

All the holes are checked with a microscope after drilling for accurate dimensions and roundness.

The water flow rate was measured through a metering tank. It was designed to absorb water surface fluctuations and free vortices and thus provides accurate flow rate measurements. For this purpose three calibrated orifices with diameters 10, 13.2 and 19.2 mm were used to cover the whole range of water flow rates. The head inside the tank was measured using a calibrated, graduated, glass tube, indicating directly the water flow rate.

The procedure followed in performing a complete experimental run is given in detail by Fahmy (1997).

In the present study, the water head over the orifice varied by ±0.5 cm. This gives an uncertainty of ±2% in the water flow rate. The uncertainty in measuring the air temperature was ±0.5°C and the uncertainty in measuring the air pressure was ±2.5 kPa. This resulted in a maximum equivalent uncertainty in the air flow rate of ±3%. The uncertainty in the pump efficiency can be computed as ±4%.

3. Results and discussion

The present study deals with different methods of air injection into the riser tube of an air lift pump (200 cm long and 25.4 mm diameter) at different values of the air injection pressure (from 0.2 to 0.4 bar) and various submergence ratios (from 0.5 to 0.75).

3.1. Discharge – air flow rate characteristics

In Fig. 2 the pumped water mass flow rate is plotted versus the supplied air mass flow rate for all the injection disks used, at submergence ratios 0.75, 0.7, 0.6 and 0.5. The results for all submergence ratios and all injection arrangements (different

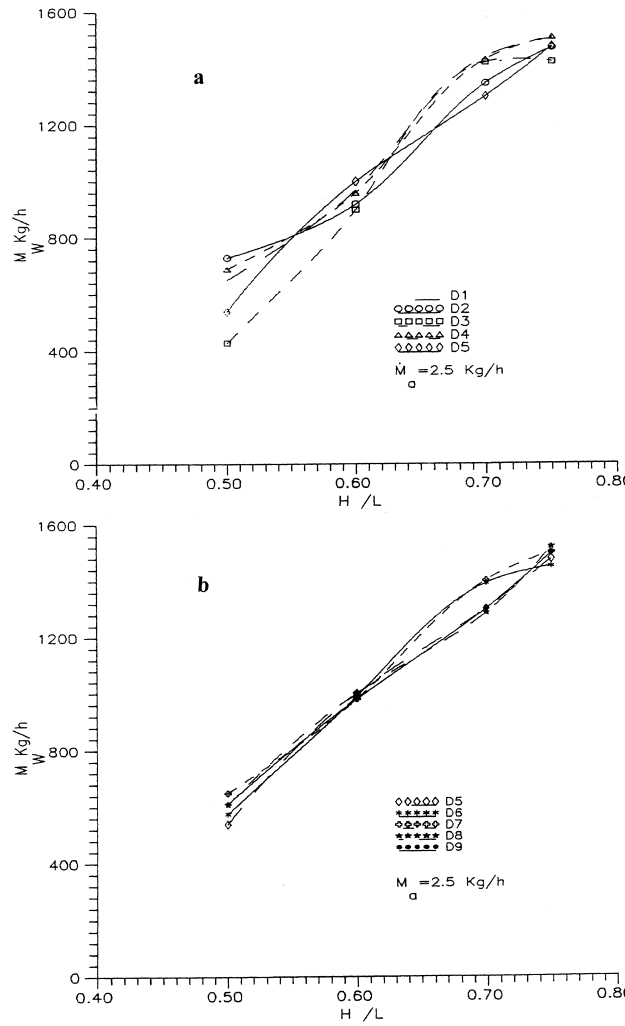

Fig. 3. Variations of pumped water versus submergence ratio, *H*/*L*, for different footpiece designs.

disks) indicate a common pattern of variation. It is clearly seen that the water mass flow rate increases with the increase of the air mass flow rate. In addition the results demonstrate that the use of different injection air nozzle footpiece designs has some effect on the performance: the experimental data tend to fall on the same characteristics pattern increasing on average. However, the values of the water flow rate at a specific air flow rate are different. In any case, the difference between the top and the bottom values, due to the use of different designs of the nozzle footpiece at the same submergence ratio, does not exceed 25%.

The results presented in Fig. 3 show the relation between the submergence ratio *H*/*L* and the pumped water discharge at a given value of the air mass flow rate for different designs of the footpiece. It is clear from this figure that for any footpiece design, as the submergence ratio increases the pumped water discharge increases. These results are expected since increasing the submergence means an increase in the pump driving power due to the difference between the bulk masses of water and water–air mixture columns, of equal heights.

3.2. Efficiency – air flow characteristics

Fig. 4 presents the experimental results of the efficiency – air flow rate characteristics at various submergence ratios *H*/*L*.

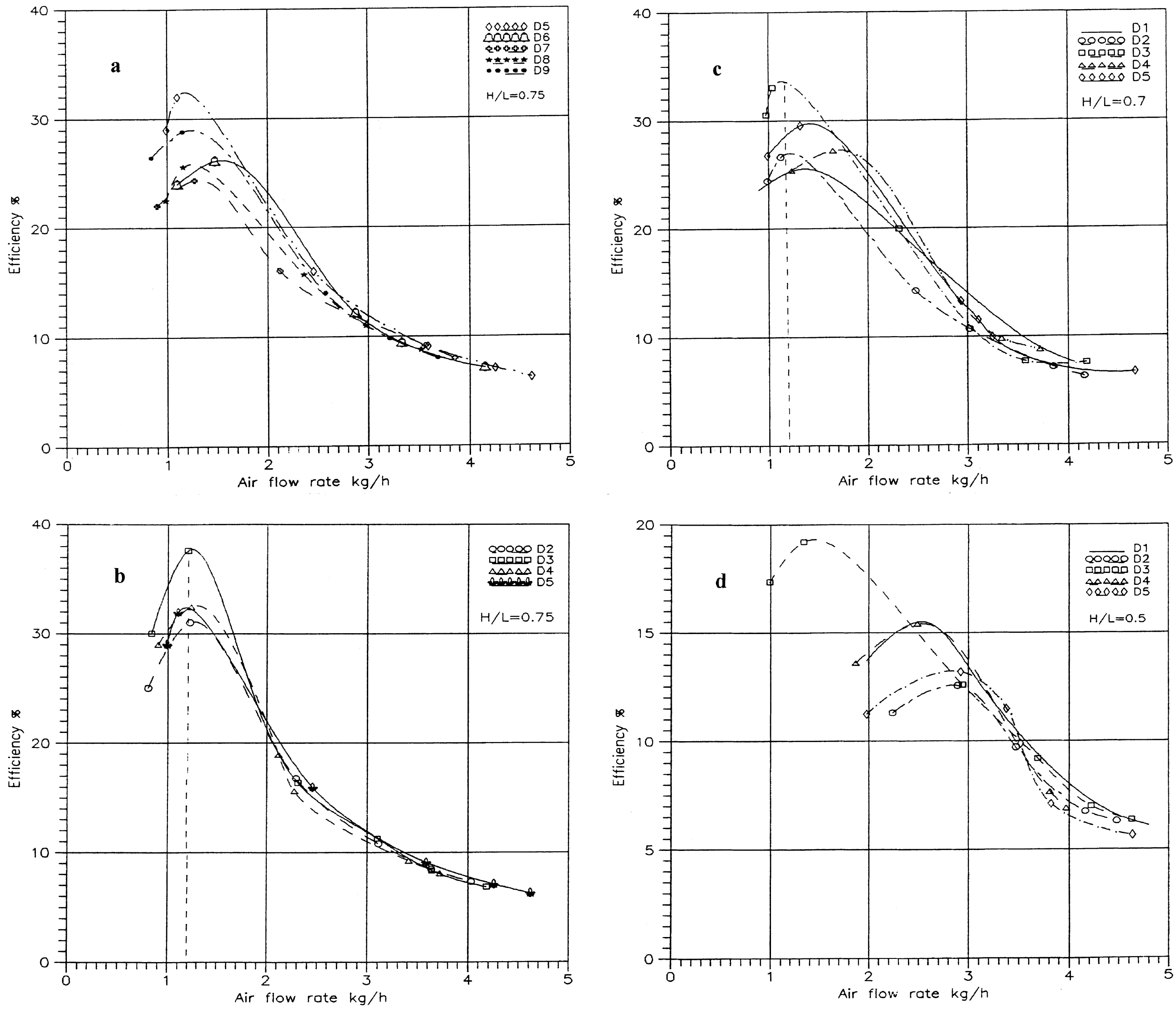

Fig. 4. Variation of pump efficiency with air flow rate for different injection disks and submergence ratios.

It is clear that as the air flow rate increases, the efficiency of the pump increases up to a certain maximum point, and after that it decreases. Fig. 4a shows that at the injection rate of 1.2 kg/h, disk No. 3 (three holes) showed the highest maximum efficiency where a maximum efficiency of 37.6% was obtained. To explain the occurrence of this highest maximum efficiency at that point, we point out that disk No. 3 having three holes leads to the creation of bubbles of good initial distribution and of suitable size to reduce the slip between air slugs and water, hence, increasing the pump efficiency. The results also show that the maximum efficiencies for different operating conditions are between two values. There are the highest maximum efficiency of 37.6% for disk No. 3 and the lowest value of 24.35% for disk No. 7 (25 holes) at an air flow rate of 1.3 kg/h. The latter efficiency is less than the highest maximum value by 13.25%. This can be attributed to the large number of holes (in disk No. 7) which produce many small air slugs with a tendency to coalesce into larger ones while ascending at small air pressure. The large slug of air resists the water flow because it occupies most of the riser cross section area, and increases the slip. Consequently the efficiency is reduced. Moreover, Fig. 4a shows that the lowest efficiencies have the tendency to combine together at a constant value of about 7%, for all air injection disks. The drop from the maximum efficiency to the lowest value occurs sharply with the increase of the air flow rate. This can be attributed to the fact that the increase of the air flow rate causes excessive accelerational loss accompanied by large values of the air void fraction at the top part of the riser. This results in more friction losses in the riser tube, and, thus, the pump efficiency is reduced. These figures also indicate that the disk with the highest efficiency is not the best disk for all conditions. For example, disk No. 6 (Fig. 4b) has an efficiency of 23.5% at an air flow rate 2 kg/h. But at the same air flow rate disk No. 3 has an efficiency of 22%. It can also be seen that there is no best disk for all the air flow rates, but at a certain air flow rate for the considered submergence ratio the highest efficiency for this specific condition can be found. It is also clear that the highest efficiency for a certain condition depends not only on the number of holes in the disk, but also on the injection air pressure and the submergence ratio; note that the curves are not parallel to each other. This may be attributed to the initial slug volume, the initial velocity and the distribution of the slugs, which have a great effect on the friction, and consequently affect the efficiency of the pump. The same

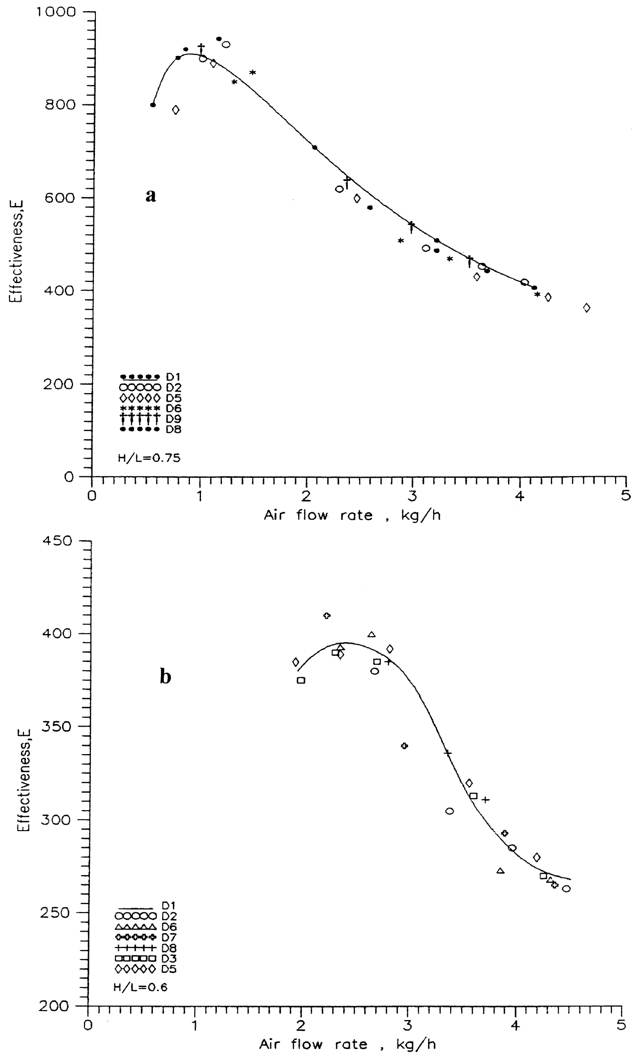

Fig. 5. Variation of pump effectiveness with air flow rate for different injection disks and submergence ratios.

characteristics are seen to exist for submergence ration $H/L = 0.7$, and 0.5, as shown in Fig. 4c and d, respectively.

3.3. *Effectiveness – air flow rate relation for different footpiece designs*

In order to obtain dimensionless parameters for the air lift pump without considering the pressure loss through the manifold behind the injection orifice, and, thus, to compare the performances of the pump when different designs of the footpiece are utilized a suitable parameter for comparison is the mass of the pumped water per unit mass of air supplied, here called the effectiveness E: E denotes water mass flow rate $\dot{M}_w$/air mass flow rate $\dot{M}_a$).

In addition, the effectiveness E allows one to compare the results for different pumps of the same construction, but with different sizes.

To clarify the trend of the data shown in Fig. 5 correlating E and the air flow rate, the data obtained with disk No. 1 (single hole) were chosen as a reference characteristic curve. All other data points, related to other footpiece disks, were plotted and found to lie around this line.

Considering the submergence ratio $H/L = 0.75$, Fig. 5a shows that the peak effectiveness is 942 at an air flow rate of 0.8 kg/h for disk No. 9 (48 holes). At higher air flow rates, this figure shows that more water was pumped but with a much lower effectiveness. Further, the experimental results of different disk designs have the same trends and the same behavior: the effectiveness increases with the increase of the air flow rate. It can also be seen that there is a significant difference, for every disk design, as of to the efficiency behavior (Fig. 4) and the effectiveness (Fig. 5a). Here, disk No. 9 has the highest effectiveness, at submergence ratio 0.75, whereas it does not have the highest efficiency at this submergence ratio. This disk, however, does not give the highest effectivenesses at other submergence ratios.

Fig. 5b demonstrates the results obtained for the effectiveness versus air mass flow rate, at another submergence ratio, namely 0.6. The data in this figure obtained with different designs of the footpiece (different disks) appear to be fairly scattered around the line exhibiting the variational characteristics of the single hole disk (D1). However, it is clear that the peak effectiveness values do not relate either to the same disk or to a fixed mass flow rate.

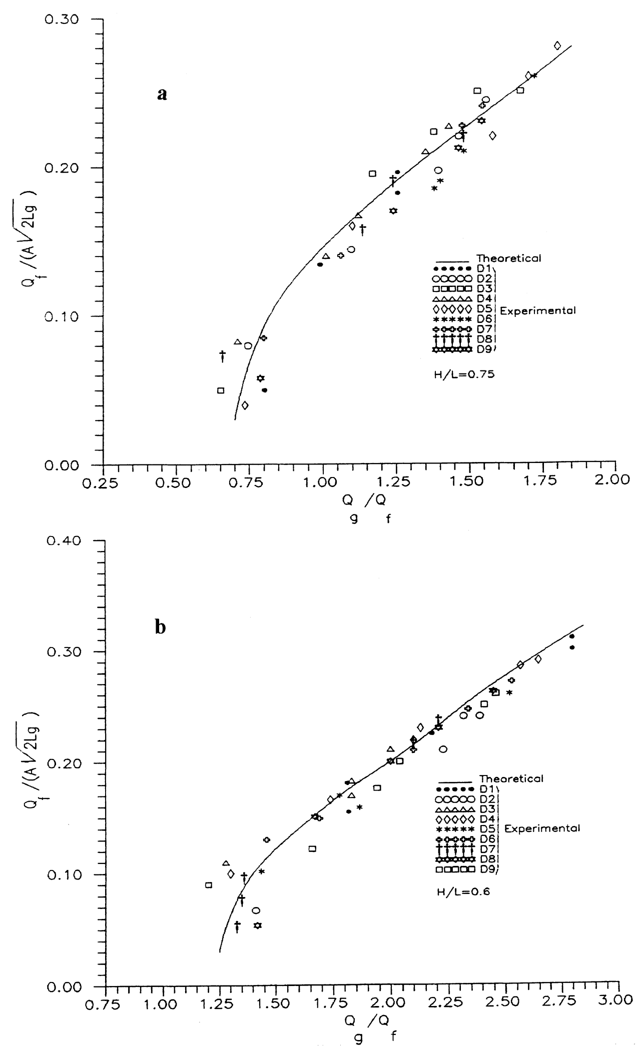

Fig. 6. Comparison between the experimental results and the one-dimensional theoretical model.

On comparing the results of the peak effectiveness and corresponding conditions (Fig. 5) with those of the highest peak efficiencies and corresponding conditions (Fig. 4), one can see clearly that the conditions for the highest peak efficiency (disk design and air mass flow rate) at any given value of the submergence ratio H/L are not the same as the conditions for the peak effectiveness value. The reasons for this are:

(i) In the first case (the relation between effectiveness and the air flow rate) only the peak effectiveness and the corresponding air mass flow rate are considered regardless of the input power for compressing the air.

(ii) In the second case (the efficiency) we have a relation between the output power (pumped water power) and the input power (compressed air power) without considering the quantities of pumped water. This means that, in the first case, at the peak effectiveness low efficiency is obtained due to a larger input power needed for air compression.

3.4. Comparisons between theoretical and experimental results

Theoretical performance curves based on the one-dimensional theory of Parker (1980) showing the relation between the dimensionless quantities $Q_f/A\sqrt{2gL}$ and Q_g/Q_f are drawn in Fig. 6, using the values for the slip S and the friction parameter K given by Parker (1980). Corresponding experimental data points for different footpiece designs and different submergence ratios are also plotted for the sake of comparison. The agreement between the experimental results and the model is seen to be rather satisfactory for all the submergence ratios under consideration.

4. Conclusions

The following conclusions can be deduced from the obtained results:

(1) The performance of the air lift pump depends upon several factors, such as footpiece design and submergence ratio. The initial bubble size and distribution in the riser section affect the air lift pump performance and a marked improvement in pump performance was obtained when using multiple-hole injectors. (An improvement in the efficiency of as much as 21% was reached with the use of a three-hole disk compared with the single-hole disk efficiency at $H/L = 0.75$.)

(2) The air injector design has a considerable effect on the water discharge as well as on the whole performance of the air lift pump.

(3) It is found to be possible to increase the quantity of pumped water by using a suitable distribution of holes in the injection disk for a certain submergence ratio.

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