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# Model Investigations of Flow Rate and Efficiency of Air Lift Pump with PM 50 Mixer and Circumferential Mixer

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## 1. Introduction

An air lift pump does not have any movable parts and it is used to lift liquids (Kujawiak et al. 2018, Kalenik 2015a) or liquid-solid mixes (Kalenik 2017). The device is built of a vertical pipe, partly submerged in liquid, where air under pressure is introduced into its lower part. During air introduction, a two-phase (liquid-air) or three-phase (liquid-air-solid) mix arises inside the vertical pipe, having lower density than the liquid (Kalenik & Chalecki 2018). As the mix within the vertical pipe becomes lighter than the surrounding liquid, the mix is pushed up by the air.

Due the simple construction and high reliability, air lift pumps are used in various applications. The air lift pumps were usually used to transport liquid both in water supply and sewage systems. Nowadays in Poland, these devices are used to lift sewage and sewage sediments in small near-home container sewage-treatment plants and big group sewage-treatment plants, i.a. in grit chambers (Sawicki 2004, Sawicki & Pawłowska 1999), as well as in high-rate filters with self-regenerating bed or for renovation of bored wells (Kalenik 2017).

The air lift pumps are also used to aerate and mix water, to remove carbon dioxide from water in industrial fish farming (Barrut et al. 2012) as well as to mix water in deep lakes and to aerate it by means of transport of water from the lake bed onto its surface (Fan et al. 2013, Qiang et al. 2018). Due to their simple construction and high reliability, the air lift pumps are applied in various branches of industry, especially in the petrochemical industry to raise oil from dead wells (Hanafizadeh et al. 2011), in the chemical industry to transport corrosive, radioactive, arid or toxic fluids (De Cachard & Delhaye 1996, Kassab et al. 2007) as well as to pump boiling fluids, where the change of liquid phase into gas phase occurs (Khalil et al. 1999). They are also used to transport suspensions in mining industry and to lift manganese concretions from deep seabed up to ca. 4000-6000 m (Kassab et al. 2007). The air lift pumps can be also used to lift leachate from drainage wells in waste disposals (Koda et al. 2017). The performed investigations (Kujawiak et al. 2020) show that domestic sewage in near-home hybrid sewage-treatment plants with moving bed are also sufficiently aerated by the air lift pump.

A two-phase (liquid-gas) or three-phase (liquid-gas-solid) flow exists in the air lift pumps which is very difficult for mathematical modeling (Kalenik & Chalecki 2018, Kalenik 2017, Ahmed et al. 2016, Kalenik 2015a, Kalenik 2015b, Nicklin 1963). Multi-phase flows occurring in various systems applied for transport of mixes are characterized by high variability of the flow rate of individual phases and depend on many factors and hydraulic variables (Kujawiak et al. 2020, Qiang et al. 2018, Kalenik 2015c, Kalenik 2014, Hu et al. 2012). The hydraulic operating conditions of two- and three-phase flow in the air lift pumps are very poorly identified. Some attempts are made to describe flow structures, occurring in various conditions of liquid-gas flow or liquid-gas-solid flow, and to work out so-called flow structure maps for them and mathematical models for simulation of flows occurring in the air lift pumps (Kalenik & Chalecki 2018, Kalenik 2017, Kalenik 2015a, Kalenik 2015b, Kim et al. 2014, Mahrous 2014, Wahba et al. 2014, Meng et al. 2013, Mahrous 2013a, Mahrous 2013b, Mahrous 2012, Kassab et al. 2009, Yoshinaga & Sato 1996, Sawicki 2004, Sawicki & Pawłowska 1999).

Tests of air lift pumps built of rectangular (Esen 2010) and curved pipes (Fujimoto et al. 2004) have been also carried out. The performed investigations of the air lift pumps with the curved pipes behind the air mixer show that the pumping efficiency for solid bodies significantly falls in such air lift pumps. However, if only liquid is being pumped then the air lift pump pipe curvature does not affect its efficiency (Mahrous 2013a). The performed investigations show that the air lift pumps are characterized by small working efficiency if compared to conventional pumps (Kujawiak et al. 2018, Kalenik 2015a, Kalenik 2015b, Tighzert et al. 2013, Kassab et al. 2009, Kassab et al. 2007).

There is little information in the technical and scientific literature on principles of calculations of water flow rate $Q_w$ in air lift pumps for a given mixer type (Kujawiak et al. 2018, Ahmed et al. 2016, Kalenik 2015a, Kalenik 2015b). Moreover, there is no information how to design mixers so as to obtain the best operating parameters of the air lift pump. From the investigations to date it arises that the mixer type and the diameter of a pressure pipe applied in a given air lift pump affect its efficiency and hydraulic operating conditions (Ahmed et al. 2016, Kalenik 2015b, Fan et al. 2013, Khalil et al. 1999). The number, diameter and distribution of holes in mixers significantly affect the type of structure of two-phase and three phase flow in the air lift pumps.

In aim to determine the efficiency of the tested air lift pump equipped with the PM 50 mixer with perforated rubber membrane as well as the circumferential mixer, the following formula has been applied (Nicklin 1963):

$$\eta = \left( \frac{\rho_w \, g \, Q_w \cdot (L - h)}{p_b \, Q_a \ln\left( \frac{p_a}{p_b} \right)} \right) 100 \tag{1}$$

where:
$\eta$ – efficiency of the air lift pump [%],
$Q_w$ – water flow rate [$m^3 \cdot s^{-1}$],
$Q_a$ – air flow rate [$m^3 \cdot s^{-1}$],
$p_a$ – air pressure [$N \cdot m^{-2}$],
$\rho_w$ – water density [$kg \cdot m^{-3}$],
$p_b$ – barometric pressure [$N \cdot m^{-2}$],
h – pressure pipe submergence length [m],
L – length of the pressure pipe till the outlet [m],
g – gravitational acceleration [$m \cdot s^{-2}$].

The paper presents the analysis of results of investigations concerning an influence of the applied constructive solutions on hydraulic operating conditions of a water-pumping air lift pump. The scope of the investigations encompassed the determination of flow rate and efficiency characteristics of an air lift pump having the discharge pipe with the internal diameter d = 0.04 m. The PM 50 mixer with a perforated rubber membrane, available on the market, as well as a mixer of own design, called circumferential mixer, were tested. The investigations were performed for three air-water mix delivery heads H: 0.40, 0.80, 1.20 m, for the specified pressure pipe submergence length h = 0.80 m.

## 2. Description of test rig

Figure 1 shows the construction and operating principle of a test rig for investigations of hydraulic operating conditions of air lift pumps. After the opening of a ball valve (2), a pipeline (1) delivered water to a tank (3). During the tests the tank (3) was permanently filled with water up to the height of 1.0 m. After the opening of another ball valve (8), the excess of the water being delivered to the tank (3) was carried by an overfall (7) to the sewerage through a floor inlet (12). A draining pipeline (10) served to empty the tank (3) from water after the ball valve (8) opening. Inside of the tank (3), at the height of 0.20 m upon its bottom, a transparent PVC discharge pipe (4) with the internal diameter of 0.04 m was mounted. The measurements of the air lift pump delivery rate were carried out for the three sand-water mix delivery heads (H): 0.40 m, 0.80 m, 1.2 m, measured over the water level in the tank (3). In the discharge pipe (4), at the height of 0.30 m over its lower edge, an air mixer (9) was mounted. In aim to measure water temperature in the tank (3), an electronic resistance thermometer (17) was applied.

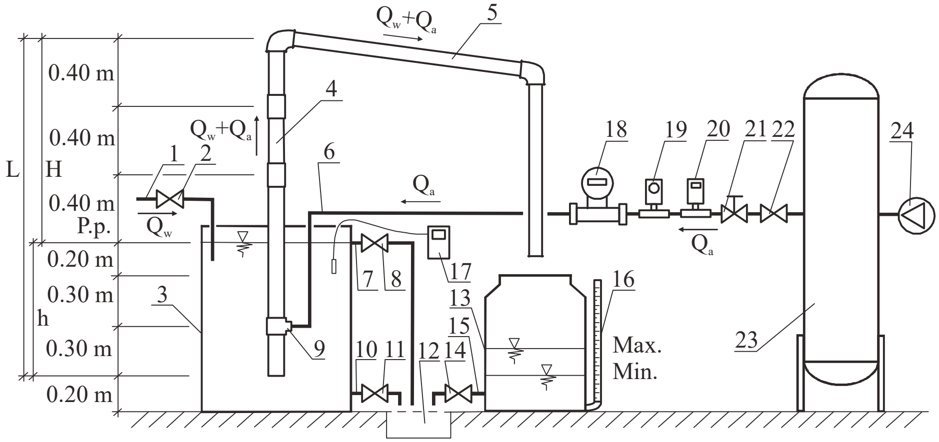


**Fig. 1.** Scheme of the air lift pump test rig: 1 – water supplying pipe, 2, 8, 11, 14, 22 – ball cut-off valve, 3 – tank with water, 4 – discharge pipe, 5 – water and air channeling pipe, 6 – air supplying pipe, 7 – overfall, 9 – mixer, 10, 15 – draining pipe, 12 – floor inlet, 13 – measuring container, 16 – scaled water level gauge, 17, 20 – electronic resistance thermometer, 18 – electromagnetic air flow meter, 19 – piezoelectric pressure sensor, 21 – needle valve, 23 – compressed air container, 24 – compressor, h – discharge pipe submergence length, L – discharge pipe length-to-outlet, H – water-air mix delivery head

Figures 2a, b show a constructive solution of the tested Aquatech PM 50 mixer equipped with a perforated rubber membrane (4), denoted hereinafter as M1, whereas Figures 2c, d – a circumferential mixer of own design, denoted hereinafter as M2. The M1 mixer had n = 8 holes having the total area A = 25.12 mm$^2$, the M1 mixer – n = 8 holes with the total area A = 25.12 mm$^2$. An elastic pipe (6) with the internal diameter of 0.013 m supplied air to the mixer (9, Fig. 1) from a compressed air container (23) where the air was pressured by a compressor (24). At the air supplying pipe (6) an electromagnetic air flow meter (18), piezoelectric pressure sensor (19), electronic resistance thermometer (20) measuring air temperature as well as a needle valve (21) and ball cut-off valve (22) were mounted.

The investigations were performed with use of Endress & Hauser devices. The measurement range of the electromagnetic air flow meter (18) was 0.0 to 30.0 $m^3 \cdot h^{-1}$ and the measurement range of the piezoelectric pressure sensor (20) – 0.0 to 400 kPa. According to the Endress & Hauser catalogue, the measurement error of the applied electromagnetic air flow meter and piezoelectric pressure sensor is lower than 1% and the output current signal falls into the range 4-20 mA. The measurement accuracy of the applied thermometer, however, was ±1°C and its measurement resolution – 0.1°C.

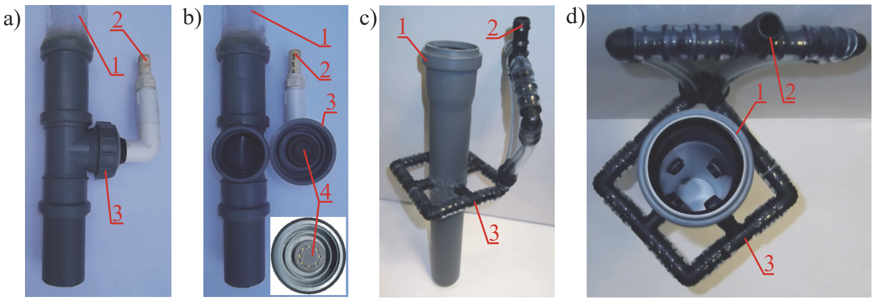


**Fig. 2.** Designs of mixers: a), b) PM 50 mixer with perforated rubber membrane (M1), c), d) circumferential mixer (M2), 1 – discharge pipe, 2 – air supplying pipe connecting tip, 3 – mixer, 4 – perforated rubber membrane

The measurements concerned water and air temperature, air pressure, barometric pressure, air flow rate, water volume and air lift pump operating time. The needle valve (21) was used to regulate the air pressure.

In aim to measure the water flow rate $Q_w$ in the air lift pump delivery rate, the measuring vessel method was applied, i.e. a plastic measuring container (13), scaled at each 1 $dm^3$, was used. The measuring container (13) capacity scale was put on the transparent water-level gauge (16), mounted at the side of the measuring container. Such solution allowed very precise reading of the volume of the water lifted by the air lift pump per time unit. For a specified delivery head H, the pumped water flew down through the channeling pipe (5) with the internal diameter d = 0.04 m to the measuring container (13). The water flow in the channeling pipe (5) was pressure-less (gravitational). In this aim, little holes serving to discharge the pumped air outside the pipe (5) were drilled in the upper wall of the channeling pipe (5). Table 1 presents assumptions for the performed experiments.

**Table 1.** Assumptions for the performed experiments

| Type of mixer | d [m] | H [m] | h [m] | L [m] | $h/L = S_r$* [–] | n [–] | A [$mm^2$] |
|---|---|---|---|---|---|---|---|
| M1 | 0.04 | 0.4<br>0.8<br>1.2 | 0.8 | 1.2<br>1.6<br>2.0 | 0.7<br>0.5<br>0.4 | 8 | 25.12 |
| M2 | 0.04 | 0.4<br>0.8<br>1.2 | 0.8 | 1.2<br>1.6<br>2.0 | 0.7<br>0.5<br>0.4 | 4 | 254.34 |

*$S_r$ – submergence ratio

## 3. Methodology of investigations

Before the beginning of each measurement series on the test rig (Figure 1), an actual barometric pressure ($p_b$) was measured with use of the piezoelectric pressure sensor (19). Then, on the water-level gauge (16) connected to the measuring container (13), it was marked the minimum level of a water free surface in the measuring container (13) by which the stop-watch was switched on as well as the maximum level of free surface of water by which the stop-watch was switched off. The level marked on the water-level gauge (16) scale referred to a certain water volume ($V_w$).

The measurement of the water flow rate ($Q_w$) was started from the opening the valves (2, 8), filling the tank (3) with water, turning on the compressor (24) and opening the valve (22) on the pipeline (6) supplying the mixer (9) with air. Then a demanded value of the air pressure ($p_a$) was fixed on the piezoelectric pressure sensor (19) using the needle valve (21). As the determined air pressure had been fixed, some quantity of water – depending on the air lift pump flow rate – flew out from the tank (3). In aim to make the measurement reliable, the water level in the tank (3) had to be kept constant. Changes of the submergence of the mixer (9) or water level changes in the tank (3) evoke significant changes in the air lift pump flow rate. The constant water level in the tank (3) was kept with use of the valve (2) placed on the discharge pipe (1) supplying water to the tank (3). Each time the valve (2) was set in the position which balanced the water flux through the channeling pipe (5) for a given value of the air pressure. Observations and regulations of the water level in the tank (3) were performed relatively to the level in the overfall (7) channeling the water excess. As these actions were completed and the working conditions of the air lift pump stabilized, the measurement started. At first, for a specified value of the air pressure, the air flow rate ($Q_a$) was being read from the electromagnetic air flow meter (18) and the air and water temperatures – from the electronic resistance thermometers (17 – water, 20 – air). As the water-level gauge (16) showed that the water free surface in the measuring container (13) reached the marked minimum level, then, during the measurement of the water flow rate $Q_w$, the stop-watch was switched on and measured a container (13) filling time (t) till the moment when the water free surface reached the marked maximum level – then the stop-watch was switched off and the needle valve (21), cutting off the air from the mixer (9), was turned off.

Then the measuring container (13) was emptied, a next value of the air pressure was set on the piezoelectric pressure sensor (19) and a next measurement started. The measurements were carried out for specified values of the air pressure ($p_a$), established between 105 and 200 kPa with intervals 5 kPa. The water flow rate ($Q_w$) was calculated by dividing the volume ($V_w$) of the water being in the measuring container (13) for the filling time (*t*). During the tests, five measurement series were carried out – each of them for each established value of the air pressure ($p_a$) and for all three water delivery heads (H): 0.40 m, 0.80 m, 1.20 m measured relatively to the water free surface in the tank (3).

## 4. Results and discussion

During the operation of the air lift pump (Fig. 1) with the perforated rubber membrane mixer M1 (Fig. 2a, b), the air flow observed in the transparent discharge pipe had a form of very fine air bubbles creating air-water emulsion with water in the whole cross section of the discharge pipe (Fig. 3a). The stream of water flowing out from the air lift pump was almost continuous, with small pulsation visible. However, during the operation of the air lift pump with the circumferential mixer M2 (Fig. 2c, d), the air flow observed in the transparent discharge pipe had a form of fine irregular bubbles which filled only a part of the discharge pipe cross section and almost evenly lifted water up (Fig. 3b). The stream of water flowing out from the air lift pump was not continuous but broken and had a pulsating character.

a)

b)

**Fig. 3.** Flow structures of air-water mix in the discharge pipe during operations of the air lift pump with: a) PM 50 mixer with perforated rubber membrane (M1), b) circumferential mixer (M2)

Figure 4 presents the distribution of the air flow rate $Q_a$ in the mixer M1 with perforated rubber membrane and circumferential mixer M2 as a function of the established air pressure value $p_a$ and the air-water mix delivery head H. Analysis of the obtained results allows to state that the air flow rate increased along with the increase of the air pressure in both of the mixer types in the air lift pump. Moreover, for a constant submergence of the mixer and specified values of the air pressure, the increase of the air-water mix delivery head had very small influence on the fall of the air pressure in these two types of mixers. Regardless the air-water mix delivery head, the values of the air flow rate by the specified air pressure were comparable for both of the mixer types what resulted from big amount of air. For the circumferential mixer, however, when the value of the air pressure was lower than $p_a = 170$ kPa, then the air flow rate $Q_a$ values were higher, whereas for the perforated rubber membrane mixer they were lower. When, in turn, the value of the air pressure exceeded $p_a = 170$ kPa, the situation was opposite. It was caused by hydraulic resistance occurring during the air flow through the mixer – higher for the perforated rubber membrane mixer than for the circumferential mixer.

A statistical analysis was also performed in aim to check whether the differences between the mean values in the results of the air flow rate $Q_a$ for the perforated rubber membrane mixer M1 and for the circumferential mixer M2 (Fig. 4) are statistically significant. Firstly, the normality of distribution was checked with use of the Shapiro-Wilk test and then the homogeneity of variance with use of the Levene test. Calculations of normality of distributions and homogeneity of variances were made with the STATISTICA software. In both tests for individual groups the value of calculated probability $p_{cal.}$ is greater than the assumed significance level $\alpha = 0.05$, which means that the conditions of normal distribution and homogeneity of variance in the examined groups are satisfied. Then, the t-Student test was used for two populations; a zero hypothesis ($H_0$: $n_1 = n_2$) stated that the mean values are statistically equal, an alternative hypothesis ($H_1$: $n_1 \neq n_2$) stated that the mean values are statistically different. Calculations of the t-Student statistics value $|t_{cal.}|$ were performed with the computer software STATISTICA; obtained results are gathered in Table 2.

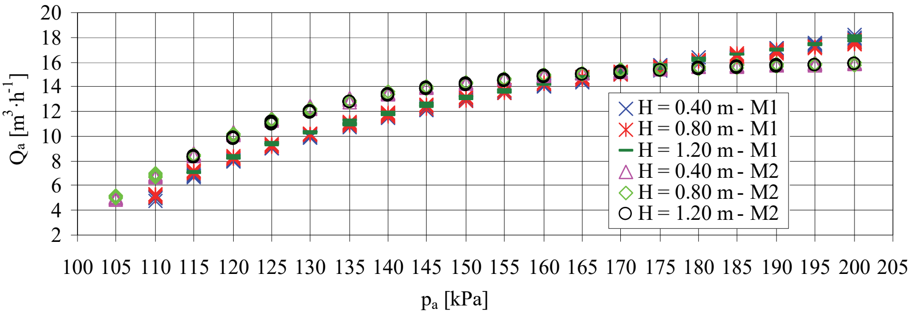


**Fig. 4.** Dependence of air flow rate $Q_a$ in the air lift pump on air pressure $p_a$ and water delivery head H for the perforated rubber membrane mixer M1 and the circumferential mixer M2

For the alternative hypothesis, it was determined a critical region $|t_{cal.}| \geq t_{\alpha=0.05}$ and, for $v = n_1 + n_2 - 2 = 36$ degrees of freedom and $\alpha = 0.05$, i.e. selected 5-percentage risk of error (significance level), the critical value $t_{\alpha=0.05} = 2.028$ was read from the tables. Analysis of Table 1 allows to state that $|t_{cal.}| \leq t_{\alpha=0.05}$, i.e. the zero hypothesis cannot be rejected, thus the differences between the mean values in the results of the air flow rate $Q_a$ for the perforated rubber membrane mixer M1 and for the circumferential mixer M2 are statistically insignificant, hence the mean values are statistically equal to each other. This is also confirmed by the calculated probability value – $p_{cal.}$ is greater than 0.05 (assumed significance level, Table 2).

**Table 2.** Results of calculations of the statistics from the t-Student test for $Q_a$. Differences between the mean values are significant with the probability $p < 0.05$

| Parameter | Mean | Standard deviation | Calculated value of the t-Student test $\lvert t_{cal.}\rvert$ | Calculated probability value $p_{cal.}$ | Value of the t-Student test read from the tables for p = 0.05 i v = 36 $t_{\alpha = 0.05}$ |
|---|---|---|---|---|---|
| $Q_a$ for M1* | 12.92 | 3.69 | 0.144 | 0.89 | 2.028 |
| $Q_a$ for M2* | 12.95 | 3.23 | | | |

* M1 – perforated rubber membrane mixer, M2 – circumferential mixer

Figure 5 presents results of measurements of the water flow rate $Q_w$ in relation to the air flow rate $Q_a$ and air-water mix delivery head H over the submergence ratio $S_r$ for both of the mixer types. Analysis of these results allows to state that the water flow rate $Q_w$ in the air lift pump decreased when the air-water mix delivery head increased, whereas $Q_w$ increased when the air flow rate $Q_a$, i.e. the specified value of the air pressure $p_a$, increased. In aim to enable the water outflow from the air lift pump on a demanded delivery head, it must be provided an appropriate minimum air flow rate $Q_{amin.}$ what forces an appropriate air pressure $p_{amin.}$. When the air-water mix delivery head increased, the minimum demanded air pressure in the discharge pipe grew for both of the mixer types. In the air lift pump with the perforated rubber membrane mixer (Figs. 1 and 2a, b), for the delivery head H = 0.40 m, the demanded average minimum air flow rate $Q_{amin.}$ was equal to 5.00 $m^3 \cdot h^{-1}$, what corresponded to the average minimum air pressure $p_{amin.}$ = 110 kPa. For the delivery head H = 0.8 m: $Q_{amin.}$ = 5.24 $m^3 \cdot h^{-1}$ and $p_{amin.}$ = 110 kPa; for H = 1.2 m: $Q_{amin.}$ = 7.01 $m^3 \cdot h^{-1}$ and $p_{amin.}$ = 115 kPa. For the circumferential mixer, however (Figs. 1 and 2c, d), for the delivery head H = 0.40 m, the demanded average minimum air flow rate $Q_{amin.}$ was equal 5.00 $m^3 \cdot h^{-1}$, what corresponded to the average minimum air pressure $p_{amin.}$ = 105 kPa. For the delivery head H = 0.8 m: $Q_{amin.}$ = 5.11 $m^3 \cdot h^{-1}$ and $p_{amin.}$ = 105 kPa; for H = 1.2 m: $Q_{amin.}$ = 8.28 $m^3 \cdot h^{-1}$ and $p_{amin.}$ = 115 kPa.

If the perforated rubber membrane mixer was applied in the investigated air lift pump and, for the specified air-water mix delivery heads H: 0.40, 0.80, 1.20 m, if the average air flow rate exceeded the value $Q_a$ = 16.0 $m^3 \cdot h^{-1}$ what corresponded to the specified air pressure $p_a$ = 180 kPa, then the water flow rate $Q_w$ in the air lift pump decreased instead of growing. The same behavior of the water flow rate $Q_w$ in the air lift pump was observed for the circumferential mixer when the average air flow rate exceeded the value $Q_a$ = 15.0 $m^3 \cdot h^{-1}$ what corresponded to the specified air pressure $p_a$ = 165 kPa. This phenomenon is well known and described both for the two-phase flow (air-water) and three-phase flow (water-sand-air) (Kassab et al. 2009, Hanafizadeh et al. 2011, Meng et al. 2013, Kalenik 2015b, Kalenik 2015c, Kalenik 2017, Ahmed et al. 2016, Kalenik & Chalecki 2018). It means that if the discharge pipe submergence length h for the investigated air lift pump is equal to 0.80 m (Fig. 1), then the maximum air flow rate $Q_a$ required for water pumping should not exceed 16.0 $m^3 \cdot h^{-1}$ if the perforated rubber membrane mixer M1 (Fig. 2a, b) is applied and 15.0 $m^3 \cdot h^{-1}$ if the circumferential mixer M2 (Fig. 2cd) is applied.

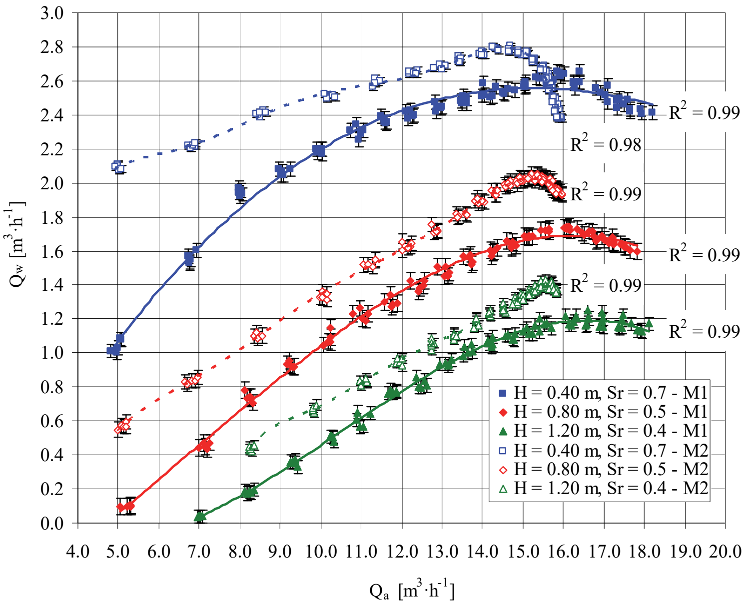


**Fig. 5.** Dependence of the water flow rate $Q_w$ on the air flow rate $Q_a$ for the perforated rubber membrane mixer M1 and the circumferential mixer M2

An abrupt fall of curves of the water flow rate $Q_w$ for the M2 mixer, visible in Fig. 5, was evoked by a significant growth in the air slip velocity in the discharge pipe of the air mixer. Due to differences between the volume and viscosity of air and water, the air in the air mixer discharge pipe flew with much higher velocity than the water what evoked a phenomenon of phase slip which is characterized by the air slip velocity. The phase slip phenomenon causes the abrupt fall of the water flow rate if the air flow rate grows (Tighzert et al. 2013).

Figure 5 presents also the trend lines, standard error bars as well as determination coefficients $R^2$ for the values of $Q_w$. The functional relation between the water flow rate and air flow rate for both of the mixer types presented a nonlinear trend and the regression (trend) type was a 6$^{th}$ degree polynomial within the range of the values of $Q_w$ obtained from the measurements. The trend lines for the values of $Q_w$ placed parallel to each other along with the increase of the air-water mix delivery head H. The values of the coefficient $R^2$ were over 0.98, what suggests that the water flow rate in the air lift pump at least in 98% depended mainly on the air flow rate, hence the specified air pressure and air-water mix delivery head, and only in 2% on remaining factors, e.g. air and water density, discharge pipe roughness or gravitational acceleration.

The standard error bars, marked in Fig. 5 for the values of $Q_w$, are very small. In case of the perforated rubber membrane mixer M1, the standard error for the values of $Q_w$ fluctuated between 0.2% and 6.7% (1.8% in average). In case of the circumferential mixer M2, however, it fluctuated between 0.1% and 3.6% (0.9% in average). The standard error was also calculated with use of the computer software STATISTICA.

Using Form. (1) and the results of measurements of the air-water mix flow rate $Q_w+Q_a$, the efficiency of the investigated air lift pump (Fig. 1) was calculated for the perforated rubber membrane mixer (Fig. 2a, b) and the circumferential mixer (Fig. 2c, d).

Analysis of these results (Fig. 6) obtained for the perforated rubber membrane mixer M1 allows to state that the efficiency $\eta$ of the air lift pump for the air-water mix delivery head H = 0.40 m decreased if the air flow rate $Q_a$, i.e. the established value of the air pressure $p_a$, increased.

For the air-water mix delivery head H equal to 0.80 m and 1.20 m, however, the efficiency $\eta$ increased at the beginning, reaching a maximum value, then decreased. In the case of the air-water mix delivery head H = 0.40 m, the investigated air lift pump achieved the highest efficiency for the average air flow rate $Q_a$ = 5.0 $m^3 \cdot h^{-1}$, i.e. for the air pressure specified as $p_a$ = 110 kPa, and this efficiency amounted $\eta$ = 9%. For the air-water mix delivery head H = 0.80 m, however, the respective values amounted $Q_a$ = 8.23 $m^3 \cdot h^{-1}$, $p_a$ = 120 kPa and $\eta$ = 3.9% and for H = 1.20 m – $Q_a$ = 11.77 $m^3 \cdot h^{-1}$, $p_a$ = 135 kPa and $\eta$ = 2.3%.

For the circumferential mixer M2, in turn, analysis of the obtained results (Fig. 6) allows to state that the efficiency $\eta$ of the air lift pump decreased along with the increase of the air flow rate $Q_a$, i.e. the specified air pressure $p_a$, for all the air-water mix delivery heads H (0.40 m, 0.80 m, 1.20 m). In case of the air-water mix delivery heads H equal to 0.40 m and 0.80 m, the investigated air lift pump achieved the highest efficiency for the average air flow rate $Q_a$ = 5.0 $m^3 \cdot h^{-1}$, hence the specified air pressure $p_a$ = 105 kPa, and this efficiency was equal to $\eta$ = 37% for H = 0.40 m and $\eta$ = 21% for H = 0.80 m. For the air-water mix delivery heads H = 1.20 m, however, the investigated air lift pump achieved the highest efficiency for the average air flow rate $Q_a$ = 8.28 $m^3 \cdot h^{-1}$, hence the specified air pressure $p_a$ = 120 kPa, and this efficiency was equal to $\eta$ = 4.4%.

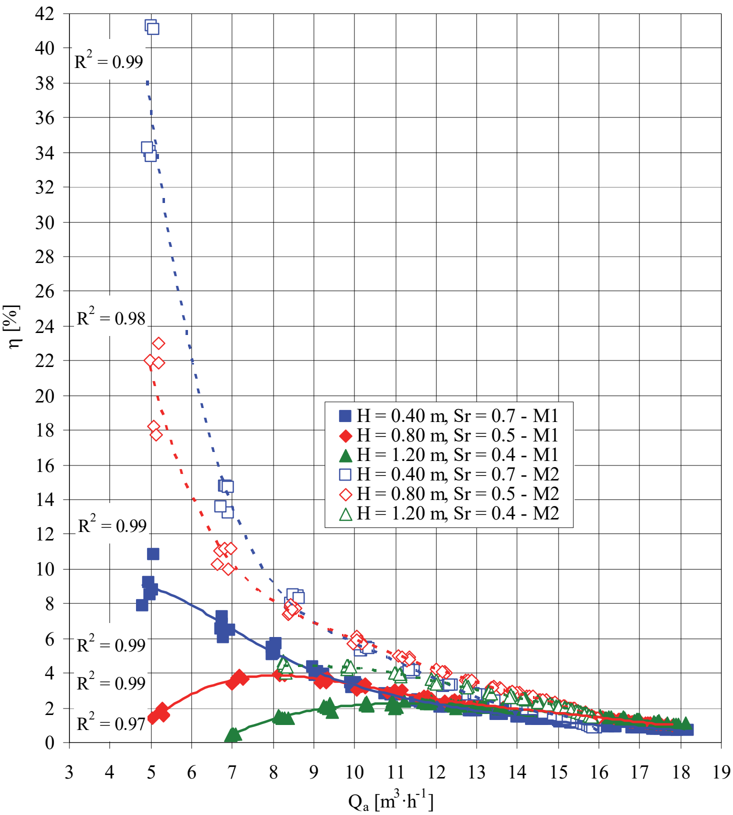


**Fig. 6.** Efficiency η of the air lift pump vs. air flow rate $Q_a$ for the perforated rubber membrane mixer M1 and the circumferential mixer M2

For the analyzed air-water mix delivery heads H, the efficiency fall was evoked by the fact that when the air flow rate $Q_a$ grew then more air bubbles appeared in the air lift pump discharge pipe occupying more space within the discharge pipe cross section and thus reducing the space occupied by water. The air flow rate increase in the discharge pipe evoked the water flow rate increase what, in turn, evoked the friction increase and fall in the efficiency of the investigated air lift pump. The efficiency η of the air lift pump for both of the mixer types decreased as well when the air-water mix delivery head H increased because the water flow rate $Q_w$ decreased. For the air lift pump with the circumferential mixer, however, higher operational efficiency η was achieved than for the air lift pump with the perforated rubber membrane mixer.

As the differences between the mean values of the results of the air flow rate $Q_a$ in case of the perforated rubber membrane mixer M1 and the air flow rate $Q_a$ in case of the circumferential mixer M2 are statistically insignificant (Table 1), i.e. the mean values are statistically equal to each other, a statistical analysis was performed in aim to check whether the differences between the mean values of the water flow rate $Q_w$ (Fig. 5) as well as the mean values of the efficiency $\eta$ (Fig. 6) for the perforated rubber membrane mixer M1 and the mean values of the water flow rate $Q_w$ as well as the efficiency $\eta$ for the circumferential mixer M2 are statistically significant for the specified air-water mix delivery heads H equal to 0.40 m, 0.80 m, 1.20 m. Firstly, as earlier, the normality of distribution was checked with use of the Shapiro-Wilk test and then the homogeneity of variance with use of the Levene test. Calculations of normality of distributions and homogeneity of variances were made with the STATISTICA software. In both tests for individual groups the value of calculated probability $p_{cal.}$ is greater than the assumed significance level $\alpha = 0.05$, which means that the conditions of normal distribution and homogeneity of variance in the examined groups are satisfied. Then, the t-Student test for two populations was applied as well and a zero hypothesis was posed ($H_0$: $n_1 = n_2$) that the mean values of $Q_w$ and the mean values of $\eta$ are statistically equal, as well as an alternative hypothesis ($H_1$: $n_1 \neq n_2$) that the mean values of $Q_w$ and the mean values of $\eta$ are statistically different. Calculations of the t-Student statistics value $|t_{cal.}|$ were also performed with use of the computer software STATISTICA and the obtained results for the water flow rate are gathered in Table 3, whereas for the efficiency $\eta$ – in Table 4.

**Table 3.** Results of calculations of the statistics for the t-Student test for $Q_w$. Differences between the mean values are significant with the probability $p < 0.05$

| Parameter | H [m] | Mean | Standard deviation | Calculated value of the t-Student test $\lvert t_{cal.}\rvert$ | Calculated probability value $p_{cal.}$ | Value of the t-Student test read from the tables for p = 0.05 and v = 36 $t_{\alpha = 0.05}$ |
|---|---|---|---|---|---|---|
| $Q_w$ for M1 | 0.40 | 2.30 | 0.41 | -4.998 | $9.33 \cdot 10^{-5}$ | 2.028 |
| $Q_w$ for M2 | | 2.60 | 0.19 | | | |
| $Q_w$ for M1 | 0.80 | 1.33 | 0.47 | -31.899 | $2.71 \cdot 10^{-17}$ | |
| $Q_w$ for M2 | | 1.71 | 0.44 | | | |
| $Q_w$ for M1 | 1.20 | 0.87 | 0.37 | -27,058 | $1.00 \cdot 10^{-3}$ | |
| $Q_w$ for M2 | | 1.17 | 0.28 | | | |

* M1 – perforated rubber membrane mixer, M2 – circumferential mixer

**Table 4.** Results of calculations of the statistics for the t-Student test for η. Differences between the mean values are significant with the probability $p < 0.05$

| Parameter | H [m] | Mean | Standard deviation | Calculated value of the t-Student test $\lvert t_{cal.} \rvert$ | Calculated probability value $p_{cal.}$ | Value of the t-Student test read from the tables for p = 0.05 and v = 36 $t_{\alpha = 0.05}$ |
|---|---|---|---|---|---|---|
| η for M1* | 0.40 | 2.56 | 2.21 | -3.562 | $5.79 \cdot 10^{-4}$ | 2.028 |
| η for M2* | | 4.87 | 8.27 | | | |
| η for M1* | 0.80 | 2.17 | 0.91 | -2.200 | $4.11 \cdot 10^{-2}$ | |
| η for M2* | | 4.37 | 4.59 | | | |
| η for M1* | 1.20 | 1.68 | 0.48 | -3.655 | $1.96 \cdot 10^{-3}$ | |
| η for M2* | | 2.57 | 0.96 | | | |

* M1 – perforated rubber membrane mixer, M2 – circumferential mixer

For the alternative hypothesis, a critical region $\lvert t_{cal.} \rvert \geq t_{\alpha=0.05}$ was determined and for $v = n_1 + n_2 - 2 = 36$ degrees of freedom and $\alpha = 0.05$, i.e. selected 5-percentage risk of error (significance level), the critical value $t_{\alpha=0.05} = 2.028$ was read from the *t*-Student distribution tables. Analysis of Tables 3 and 4 allows to state that $\lvert t_{cal.} \rvert \geq t_{\alpha=0.05}$, i.e. the zero hypothesis must be rejected, thus the differences between the mean values in the results of the air flow rate $Q_w$ as well as the efficiency η for the perforated rubber membrane mixer M1 and the air flow rate $Q_w$ as well as the efficiency η for the circumferential mixer M2 are statistically significant for the specified air-water mix delivery heads 0.40 m, 0.80 m and 1.20 m. This is also confirmed by the calculated probability value – $p_{cal.}$ is lower than 0.05 (assumed significance level, Tables 3 and 4).

The obtained results show that the type of an applied mixer strongly affects the flow rate and efficiency of the air lift pump – it is confirmed also by other scientists (Qiang et al. 2018, Ahmed et al. 2016).

## 5. Summary

In the investigated air lift pump, for both of the mixer types (perforated rubber membrane mixer and circumferential mixer), the air flow rate $Q_a$ increased when the value of the air pressure $p_a$ was specified on a higher level. When the air flow rate $Q_a$ increased, the water flow rate $Q_w$ also increased reaching maximum, then felt. For both of the mixer types, however, the water flow rate $Q_w$ decreased when the air-water mix delivery head H increased.

In the investigated air lift pump with the discharge pipe with the internal diameter $d = 0.04$ m and constant discharge pipe submergence length $h = 0.80$ m, for both of the mixer types, the water flow rate increased along with the increase of the air flow rate and it amounted between 5.0 $m^3 \cdot h^{-1}$ and 16.0 $m^3 \cdot h^{-1}$ in average for the perforated rubber membrane mixer and between 5.0 $m^3 \cdot h^{-1}$ and 15.0 $m^3 \cdot h^{-1}$ in average for the circumferential mixer. For higher air flow rates, however, the water flow rate decreased for both of the mixer types. In this respect, it is recommended that, during pumping in such a device, the air flow rate is no lower than 5.0 $m^3 \cdot h^{-1}$ and no higher than 16.0 $m^3 \cdot h^{-1}$ for the perforated rubber membrane mixer, whereas it is no lower than 5.0 $m^3 \cdot h^{-1}$ and no higher than 15.0 $m^3 \cdot h^{-1}$ for the circumferential mixer.

The efficiency $\eta$ of the air lift pump for both of the mixer types decreased if the air-water mix delivery head H increased. For the air lift pump with the circumferential mixer, however, a higher efficiency $\eta$ was achieved than for the air lift pump with the perforated rubber membrane mixer.

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## Abstract

The paper presents the analysis of results of investigations concerning an influence of applied constructive solutions on hydraulic operating conditions of a water-pumping air lift pump. The scope of the investigations encompassed the determination of flow rate and efficiency characteristics of an air lift pump having the discharge pipe with the internal diameter d = 0.04 m. The PM 50 mixer with a perforated rubber membrane, available on the market, as well as a mixer of own design, called circumferential mixer, were tested (the name origins from the fact that the mixer has the shape of a ring which encloses the discharge pipe on its whole circumference). The investigations were performed for three air-water mix delivery heads H: 0.40, 0.80, 1.20 m, for the specified pressure pipe submergence length h = 0.80 m. It has been stated that for both types of the applied mixers the water flow rate $Q_w$ increased along with the increase of the air flow rate $Q_{a,}$ reaching maximum, then decreased. However, in both of the applied mixers, the water flow rate $Q_w$ permanently decreased as the air-water mix delivery head H increased. The air lift pump achieved higher water flow rate $Q_w$ if the circumferential mixer was applied instead of that with perforated rubber membrane. It has been proved that for both of the applied types of mixers the air flow rate $Q_a$ in the air lift pump cannot be lower during water pumping than 5.0 $m^3 \cdot h^{-1}$ and should not exceed 15.0 $m^3 \cdot h^{-1}$ in case of the circumferential mixer and 16.0 $m^3 \cdot h^{-1}$ for the perforated rubber membrane mixer. The efficiency $\eta$ of the tested air lift pump for both of the applied types of mixers decreased when the air-water mix delivery head H increased. The higher efficiency $\eta$, however, was obtained for the air lift pump with the circumferential mixer than for the perforated rubber membrane mixer.

**Keywords:**
air lift pump, perforated rubber membrane mixer, circumferential mixer, two-phase flow

# Badania modelowe wydajności i sprawności pracy powietrznego podnośnika z mieszaczem typu PM 50 i z mieszaczem obwodowym


## Streszczenie

W artykule przedstawiono analizę wyników badań, dotyczących wpływu stosowanych rozwiązań konstrukcyjnych mieszaczy na hydrauliczne warunki pracy powietrznego podnośnika do tłoczenia wody. Zakres badań obejmował wyznaczenie charakterystyk wydajności i sprawności pracy powietrznego podnośnika o średnicy wewnętrznej rurociągu tłocznego d = 0,04 m. Do badań wykorzystano mieszacz dostępny na rynku typu PM 50 z perforowaną gumową membraną i mieszacz własnej konstrukcji, który nazwano mieszaczem obwodowym (nazwa pochodzi stąd, że ma on kształt pierścienia, który obejmuje rurociąg tłoczny na całym jego obwodzie). Badania wykonano dla trzech wysokości podnoszenia mieszaniny wody i powietrza H: 0,40, 0,80, 1,20 m, przy stałej długość zanurzenia rurociągu tłocznego h = 0,80 m. Stwierdzono, że dla obu zastosowanych typów mieszaczy natężenie przepływu wody $Q_w$ rosło wraz ze wzrostem natężenia przepływu powietrza $Q_a$ osiągając maksimum, a następnie malało. Natomiast w obu zastosowanych typach mieszaczy wraz ze wzrostem wysokości podnoszenia mieszaniny wody i powietrza H, natężenie przepływu wody $Q_w$ tylko malało. Większą wydajność natężenia przepływu wody $Q_w$ powietrzny podnośnik uzyskał z mieszaczem obwodowym niż z mieszaczem z perforowaną gumową membraną. Wykazano, że dla obu zastosowanych typów mieszaczy natężenie przepływu powietrza $Q_a$ w powietrznym podnośniku podczas tłoczenia wody nie może być mniejsze niż 5,0 $m^3 \cdot h^{-1}$ i nie powinno przekraczać dla mieszacza obwodowego 15,0 $m^3 \cdot h^{-1}$, a dla mieszacza z perforowaną gumową membraną 16,0 $m^3 \cdot h^{-1}$. Sprawność pracy $\eta$ badanego powietrznego podnośnika dla obu zastosowanych mieszaczy malała wraz ze wzrostem wysokości podnoszenia mieszaniny wody i powietrza H. Natomiast dla powietrznego podnośnika z mieszaczem obwodowym uzyskano większą sprawność pracy $\eta$, niż dla powietrznego podnośnika z mieszaczem z perforowaną gumową membraną.



**Słowa kluczowe:**
powietrzny podnośnik, mieszacz z perforowaną gumową membraną,
mieszacz obwodowy, przepływ dwufazowy