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# EFFECT OF THE NUMBER OF CARBON ATOMS IN AN ALCOHOL ON THE GAS HOLDUP PROFILES IN A BUBBLE COLUMN OPERATED IN THE HOMOGENEOUS REGIME

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Bubble columns (BCs) are widely used in the chemical industry. Their operation with an air-water system at ambient conditions is very well investigated. However, when different alcohols are mixed with water, the BC hydrodynamics becomes much more complicated and the gas holdups cannot be predicted by means of the existing empirical correlations. In this work the effect of the number of carbon atoms in an alcohol on the gas holdup profiles in a BC (0.1 m in ID) equipped with a perforated plate gas sparger (96 orifices with 1 mm ID) was studied. Aqueous solutions of three alcohols (1-butanol, 2-pentanol and 3-hexanol) were investigated. The results in this article show that the number of carbon atoms in an alcohol is an important factor and it should be included in any reliable empirical correlation for gas holdup prediction. This is the main objective of the current research.

*Keywords:* bubble column, aqueous solutions of alcohols, gas holdup profiles, number of carbon atoms

## 1. INTRODUCTION

Bubble columns (BCs) are widely used in the chemical industry, petrochemistry, biochemistry, wastewater treatment, flotation, etc. Their main advantages are ease of construction, low number of mechanical components, efficient mass and heat transfer, good mixing, high thermal stability, low operating costs and energy requirements, etc. The nature of the gas-liquid system has a substantial influence on the character of the dispersion and on the efficiency of the phase contact in BCs.

The addition of surface active agents like alcohols reduces the surface tension of the liquid and leads to the formation of smaller bubbles. They increase the bubble residence time in the column and ultimately they increase the gas holdup. Helchi et al. [1] argue that when the liquid viscosity increases, the gas holdup decreases due to the promotion of bubble coalescence. Kelkar et al. [2] reported that the increase in the number of carbon atoms of the straight chain length for fatty alcohols leads to an increase in the gas holdup. The authors stated that the gas holdup decreased in the following order: n-butanol > n-propanol > i-propanol > ethanol > methanol > water. The addition of surface active agents, such as alcohols, which decrease the surface tension of the liquid, leads to the dominance of the non-coalescence properties, resulting in the production of smaller bubbles. The latter have larger gas holdup and surface area and longer retention time of the bubbles in the column. In the presence of alcohols the bubbles become denser and rise relatively slowly since they remain in the homogeneous regime [1]. Helchi et al. [1] argue that the formation of small bubbles delays the transition from homogeneous to heterogeneous regime as the rate of bubble coalescence decreases. The authors also found that increasing the number of orifices on the perforated plate leads to the formation of smaller bubbles and thus to an increase of the gas holdup. Several other researchers [3-6] have also studied the effect of addition of alcohols on the gas holdup in other gas-liquid contactors (annular gap bubble column, external-loop airlift reactor, split-rectangular airlift reactor, etc.). So, this topic is considered quite interesting from an industrial viewpoint for future studies.

A unified correlation for prediction of the overall gas holdups in BCs operated with various aqueous alcohol solutions is not available in the open literature. Mouza et al. [7] studied the effects of liquid properties on gas holdups in air-n-butanol and air-water systems. The authors found that alcohols with lower surface tension retained more gas. Kazakis et al. [8] reported that in the homogeneous flow regime the liquid viscosity has little effect on gas holdup. Kelkar et al. [2] proposed a gas holdup correlation for aqueous solutions of alcohols aerated with air. It is noteworthy that as parameters the carbon number and superficial liquid velocity were included. Mouza et al. [7] developed another correlation explicitly valid for air-n-butanol and air-water systems. It is noteworthy that the dimensionless ratio of the sparger diameter to the column diameter was included as a parameter. Kazakis et al. [8] developed another gas holdup correlation in which the dimensionless ratio of the porous diameter to the column diameter was considered, as well.

Helchi et al. [1] developed own gas holdup correlation and a machine learning method. The authors found that the gas holdup increase with the increase of the superficial gas velocity and the alcohol concentration. They argue that the presence of alcohol in the mixture reduces the ability of the bubbles to interconnect and leads to the stabilization of the homogeneous regime and the production of small bubbles.

In this short communication will be demonstrated that the number of carbon atoms in the alcohol has an important effect on the gas holdup profiles in a homogeneous BC (0.1 m in ID) operated with three different aqueous solutions of alcohols. Therefore, any reliable empirical correlation for gas holdup prediction should include this key parameter.

## 2. EXPERIMENTAL SETUP

The gas holdup measurements were performed in a BC (0.1 m in ID) equipped with a perforated plate gas sparger (96 orifices × ∅ 1.0 mm). The column was operated in the homogeneous regime, i.e. at superficial gas velocities below 0.06 m/s. The gas holdups were estimated visually based on the data from the clear liquid height (1.1 m) and the aerated height. These heights were estimated by means of a ruler glued to the column's wall. Each gas holdup was calculated as a ratio of the difference between aerated height and clear liquid height divided by the aerated height. The reported overall gas holdups in this work are the mean values of three measurements. The experimental error was always within ± 3.0 %.

Compressed air was used as a gas phase, whereas three alcohols (1-butanol, 2-pentanol and 3-hexanol) were used as a liquid phase. The alcohols were supplied by the company Sigma Aldrich (Germany). The names of the alcohols used in this work correspond to the labels on the bottles. The company is using the following synonyms:

1-butanol: n-butanol, butyl alcohol; 2-pentanol: sec-amyl alcohol, sec-pentyl alcohol; methyl propyl carbinol; 3-hexanol: ethyl propyl carbinol.

These alcohols were mixed with a deionized water (DW) in different concentrations: 0.5, 1.0 and 1.5 vol. %. Only in the case of 3-hexanol the highest concentration was 1.4 % due to the high cost of this alcohol. The small difference (0.1 %) is considered negligibly small in order to affect the gas holdup profile. The physicochemical properties of the various aqueous solutions of alcohols have been measured by a professional chemist and are listed in Table 1. It is clear that mainly the surface tension decreases as the alcohol concentration increases.

Tabela 1. Właściwości fizykochemiczne wodnych roztworów alkoholi stosowanych w pracy.

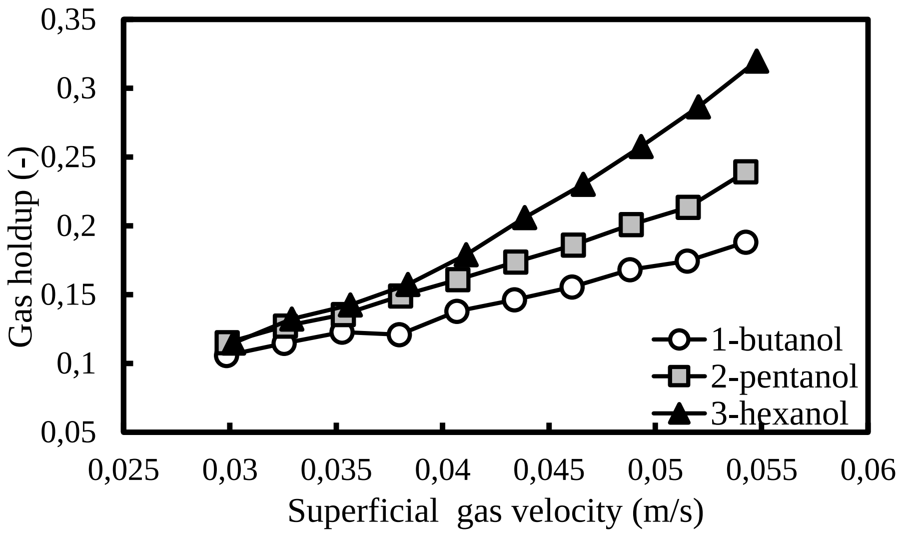
Table 1. Physicochemical properties of the aqueous solutions of alcohols used.

| **Liquid mixture** | **Density** | **Viscosity** | **Surface tension** |
|---|---|---|---|
| DW+1-butanol (0.5 vol. %) | 998.570 kg/m$^3$ | $0.863 \times 10^{-3}$ Pas | $60.95 \times 10^{-3}$ N/m |
| DW+2-pentanol (0.5 vol. %) | 998.350 kg/m$^3$ | $0.862 \times 10^{-3}$ Pas | $56.50 \times 10^{-3}$ N/m |
| DW+3-hexanol (0.5 vol. %) | 998.525 kg/m$^3$ | $0.862 \times 10^{-3}$ Pas | $51.21 \times 10^{-3}$ N/m |
| DW+1-butanol (1.0 vol. %) | 997.590 kg/m$^3$ | $0.878 \times 10^{-3}$ Pas | $59.39 \times 10^{-3}$ N/m |
| DW+2-pentanol (1.0 vol. %) | 998.025 kg/m$^3$ | $0.874 \times 10^{-3}$ Pas | $49.59 \times 10^{-3}$ N/m |
| DW+3-hexanol (1.0 vol. %) | 998.715 kg/m$^3$ | $0.871 \times 10^{-3}$ Pas | $44.13 \times 10^{-3}$ N/m |
| DW+1-butanol (1.5 vol. %) | 997.130 kg/m$^3$ | $0.890 \times 10^{-3}$ Pas | $52.57 \times 10^{-3}$ N/m |
| DW+2-pentanol (1.5 vol. %) | 997.575 kg/m$^3$ | $0.886 \times 10^{-3}$ Pas | $45.34 \times 10^{-3}$ N/m |
| DW+3-hexanol (1.4 vol. %) | 998.550 kg/m$^3$ | $0.878 \times 10^{-3}$ Pas | $41.63 \times 10^{-3}$ N/m |

It is noteworthy that this work is a continuation of the work of Zahradnik et al. [9] who studied the effect of seven alcohols on the gas holdup in viscous solutions of saccharose. They used a different column (0.15 m in ID) equipped with a different gas sparger (perforated plates with orifice diameters of 0.5 mm and 1.6 mm). The authors did not distinguish any effect of the type of alcohol or additional factors (polarity, hydrophobicity, surface mobility, solubility, bubble-coalescence properties, etc.) on the gas holdup profiles. All existing empirical correlations [10-12] also do not take into account these effects.

## 3. RESULTS AND DISCUSSION

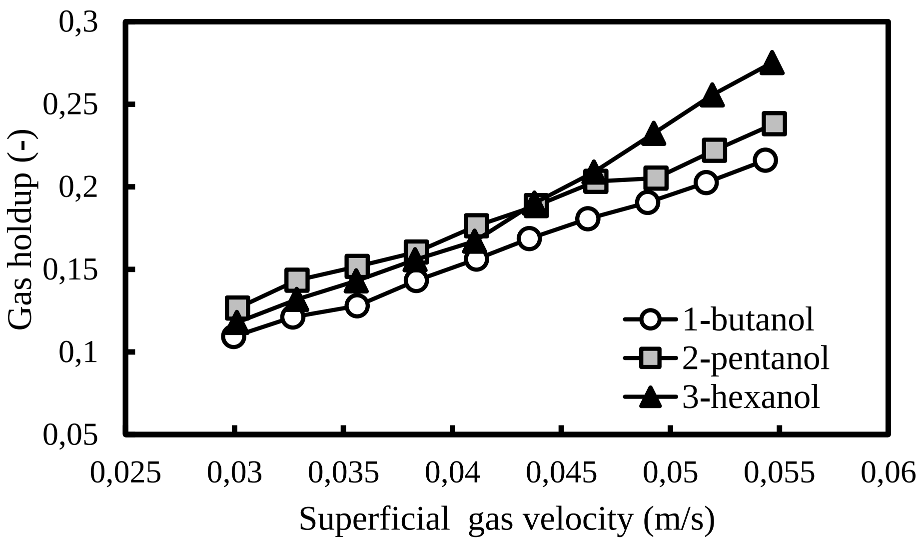
Fig. 1 shows that in the case of alcohol concentration of 0.5 vol. % the gas holdups in 3-hexanol are higher than the gas holdups in the other two alcohols. This trend is especially clear beyond superficial gas velocity of 0.04 m/s. Obviously at this alcohol concentration the increase of the carbon atoms in the alcohol leads to an increase of the gas holdup.




Rys. 1. Porównanie zatrzymywania gazu w roztworach wodnych trzech alkoholi o stężeniu 0,5% obj.

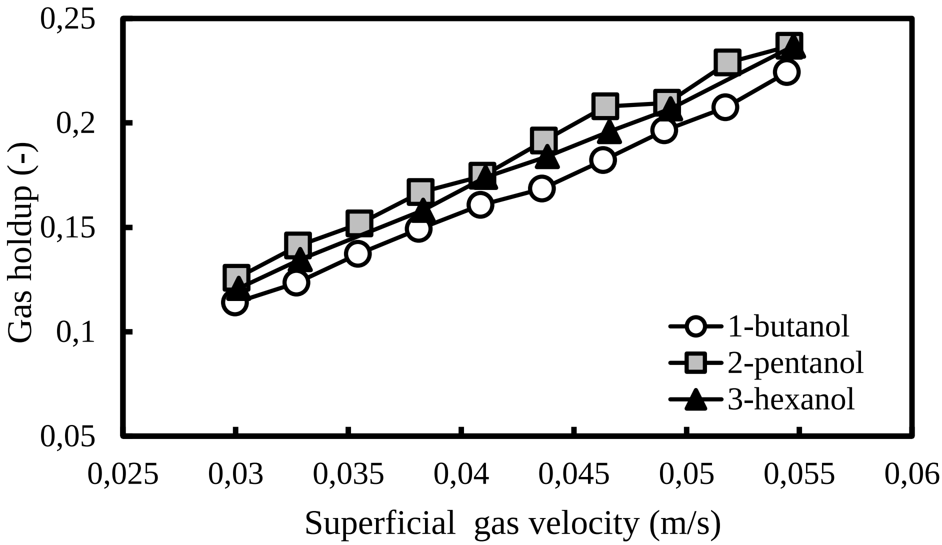
Fig. 1. Comparison of the gas holdups in three aqueous solutions of alcohols at 0.5 vol. %.

Fig. 2 shows that in the case of alcohol concentration equal to 1.0 vol. %, when the superficial gas velocity exceeds 0.045 m/s the alcohol (3-hexanol) with the highest carbon atoms exhibits the highest gas holdups and the one with the lowest carbon atoms (1-butanol) exhibits the lowest gas holdups. Below this critical gas velocity the gas holdups for 3-hexanol are in between the ones for the other two aqueous alcohol solutions. The gas holdup profile for 1-butanol monotonously increases, whereas in the case of the other two aqueous alcohol solutions there are some changes in the rate of gas holdup increase.




Rys. 2. Porównanie zatrzymywania gazu w trzech wodnych roztworach alkoholi o stężeniu 1,0% obj.

Fig. 2. Comparison of the gas holdups in three aqueous solutions of alcohols at 1.0 vol. %.




Rys. 3. Porównanie zatrzymywania gazu w trzech wodnych roztworach alkoholi o stężeniu 1,5% obj. (z wyjątkiem 3-heksanolu)

Fig. 3. Comparison of gas holdups in three aqueous solutions of alcohols at 1.5 vol. % (except for 3-hexanol)

Fig. 3 shows that when the alcohol concentration is increased to 1.5 vol. % (except for 3-hexanol), the trend between the gas holdups of 1-butanol and 2-pentanol remains the same. The gas holdups for 3-hexanol lie in between those for 1-butanol and 2-pentanol. However, it should be taken into account the fact that the concentration of 3-hexanol was 1.4 vol. % due to the higher cost of this alcohol.

In Table 2 the constants a and the exponents b, of the empirical power fit of the gas holdup as a function of the superficial gas velocity ($\varepsilon_G = aU_G^b$), in the various aqueous solutions of alcohols are listed. Such a detailed analysis of this empirical correlation in the case of various aqueous solutions of alcohols has not been performed in the literature hitherto. At a concentration of 0.5 vol. % alcohol in the mixture, the constant a increases when the number of carbon atoms in the alcohol increases. The exponent b also increases and it even goes beyond 1.2 in the case of 3-hexanol. Shah et al. [13] argue that in the homogeneous regime the exponent should vary in between 0.8 and 1.2. It is noteworthy that the exponents of both 1-butanol and 2-pentanol comply with this finding.

Tabela 2. Wartości stałej i wykładnika w różnych roztworach wodnych alkoholi.
Table 2. Values of both the constant and the exponent in various aqueous solutions of alcohols.

| **Liquid mixture** | **Constant a** | **Exponent b** |
|---|---|---|
| DW+1-butanol (0.5 vol. %) | 3.324 | 0.992 |
| DW+2-pentanol (0.5 vol. %) | 7.279 | 1.187 |
| DW+3-hexanol (0.5 vol. %) | 37.079 | 1.655 |
| DW+1-butanol (1.0 vol. %) | 6.264 | 1.157 |
| DW+2-pentanol (1.0 vol. %) | 4.479 | 1.015 |
| DW+3-hexanol (1.0 vol. %) | 17.365 | 1.436 |
| DW+1-butanol (1.5 vol. %) | 5.722 | 1.119 |
| DW+2-pentanol (1.5 vol. %) | 5.193 | 1.057 |
| DW+3-hexanol (1.4 vol. %) | 5.810 | 1.104 |

In the case of alcohol concentration of 1.0 vol. %, both the constant a and the exponent b increase as the number of carbon atoms increases except for the case of 2-pentanol. The reason for this particular deviation is unclear. The exponent for 3-hexanol is again slightly outside the upper boundary reported by Shah et al. [13].

In case of alcohol concentration of 1.5 vol. % (except for 3-hexanol), both the constants a and exponents b in all three aqueous solutions of alcohols are practically the same. The exponents are below the limit of 1.2 typical for the homogeneous regime [13]. These results show that the slightly lower concentration of 3-hexanol has practically no influence on the gas holdup profiles. The constant a in aqueous solutions of 3-hexanol with concentrations 0,5 vol. % and 1.0 vol. % are much higher than in the other aqueous alcoholic solutions.

## CONCLUSIONS

- As the number of carbon atoms in the alcohol increase, the gas holdup profile increases. Therefore, this factor should be considered in any empirical correlation;
- In all aqueous solutions of alcohols the gas holdup values increase monotonously as a function of the superficial gas velocity in the homogeneous regime;
- In the case of 1-butanol, both the constant a and the exponent b (of the empirical fit of gas holdup as a function of the superficial gas velocity) increase with the alcohol concentration;
- In the case of 3-hexanol, the exponent b (of the empirical power fit of gas holdup as a function of the superficial gas velocity) exceeded the typical value of 1.2 for the homogeneous regime for concentrations of 0.5 and 1.0 wt %.

## SYMBOLS – OZNACZENIA

A – constant in the empirical fit $\varepsilon_G = aU_G^b$ (–)

B – exponent in the empirical fit $\varepsilon_G = aU_G^b$ (–)

$U_G$ – superficial gas velocity (m/s)

$\varepsilon_G$ – overall gas holdup (–)

## ABBREVIATIONS – SKRÓTY

BC – bubble column
DW – deionized water
ID – inner diameter

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## WPŁYW LICZBY ATOMÓW WĘGLA W ALKOHOLU NA PROFILE ZATRZYMANIA GAZU W KOLUMNIE BARBOTAŻOWEJ PRACUJĄCEJ W REŻIMIE HOMOGENICZNYM

Kolumny barbotażowe są jednymi z najczęściej stosowanych aparatów gazowo-cieczowych w przemyśle chemicznym. Jednak większość dostępnych artykułów w literaturze dotyczy ich pracy w układzie powietrze-woda. W ciągu ostatnich dwóch dekad w literaturze opublikowano kilka artykułów dotyczących kolumn barbotażowych pracujących z alkoholami lub wodnymi roztworami alkoholi. Dotyczyły one głównie korelacji empirycznych opisujących zatrzymywanie gazu w kolumnach. Wpływ struktury lub rodzaju alkoholu na profile zatrzymywania gazu nie został wyczerpująco zbadany.

W niniejszym artykule przeprowadzono szczegółową analizę zachowania się zatrzymywania gazu w kolumnie barbotażowej o średnicy wewnętrznej 0,1 m, pracującej z trzema różnymi wodnymi roztworami alkoholi (1-butanolu, 2-pentanolu i 3-heksanolu). Przebadano mieszaniny wody dejonizowanej (DW) i trzech różnych stężeń rozpatrywanych alkoholi: 0,5, 1,0 i 1,5% obj. Kolumna barbotażowa była wyposażona w dystrybutor gazu w postaci perforowanej płytki (96 otworów ∅ 1 mm). Kolumna pracowała w warunkach otoczenia w jednorodnym reżimie w zakresie prędkości gazu od 0,02 do 0,06 m/s, liczonych na cały przekrój aparatu.

Stwierdzono, że we wszystkich przypadkach profile zatrzymania gazu rosły wraz ze wzrostem prędkości gazu. Przy stężeniach alkoholu 0,5 i 1,0% obj. zatrzymanie gazu rosło wraz z liczbą atomów węgla, tj. najniższe zatrzymanie gazu obserwowano w 1-butanolu, a najwyższe w 3-heksanolu. Tendencja ta była szczególnie wyraźna przy powierzchniowych prędkościach gazu powyżej 0,04 m/s. W przypadku stężenia alkoholu 1,5% obj. zatrzymanie gazu dla 3-heksanolu zawsze mieściło się pomiędzy wartościami dla pozostałych dwóch alkoholi. Jako możliwą przyczynę należy wziąć pod uwagę fakt, że stężenie 3-heksanolu wynosiło 1,35% obj., ale różnica jest pomijalnie mała.

Opracowano korelacje, opisujące zatrzymanie gazu w funkcji prędkości gazu w formie równania potęgowego. Przy stężeniu alkoholu 0,5% obj. zarówno stała, jak i wykładnik rosną wraz ze wzrostem liczby atomów węgla w alkoholu. Gdy stężenie alkoholu podwaja się do 1,0% obj., tendencja ta utrzymuje się z wyjątkiem 2-pentanolu. W przypadku stężenia alkoholu 1,5% obj. zarówno stała, jak i wykładnik są praktycznie takie same, co implikuje podobny stopień turbulencji w tych układach. Stwierdzono, że w przypadku 3-heksanolu wykładnik zawsze przekraczał wartość 1,2, co jest typowym wykładnikiem dla jednorodnego reżimu przepływu.

*Słowa kluczowe*: kolumna barbotażowa, wodne roztwory alkoholi, profile zatrzymywania gazu, liczba atomów węgla

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