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Chemical Engineering and Processing 43 (2004) 575–579

Chemical Engineering and Processing

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# Influence of scale on the volumetric mass transfer coefficients in bubble columns

C.O. Vandu, R. Krishna*

*Department of Chemical Engineering, University of Amsterdam, Nieuwe Achtergracht 166, Amsterdam WV 1018, Netherlands*

Received 19 December 2002; received in revised form 17 February 2003; accepted 17 February 2003

**Abstract**

The gas holdup, $\varepsilon$, and volumetric mass transfer coefficient, $k_La$, were measured for the air–water system in bubble columns of three different diameters, 0.1, 0.15 and 0.38 m. The superficial gas velocity $U$ was varied in the range 0–0.35 m s$^{-1}$, spanning both the homogeneous and heterogeneous flow regimes. The gas holdup $\varepsilon$ shows a small decrease with increased column diameter; this effect is due to increased liquid recirculations with increasing scale. The volumetric mass-transfer coefficient, $k_La$, closely follows the trend in gas holdup. For $U > 0.08$ m s$^{-1}$, the value of $k_La/\varepsilon$ was found to be practically independent of column diameter *and* superficial gas velocity; the value of this parameter is found to be about 0.48 s$^{-1}$. Our studies provide a simple method for estimation of $k_La$ in industrial size bubble columns operated at high superficial gas velocities.

*Keywords:* Volumetric mass transfer coefficients; Bubble columns; Gas holdup

## 1. Introduction

Bubble columns are widely used in industry for carrying out a variety of chemical reactions such as hydrogenations, oxidations and the Fischer–Tropsch synthesis. For successful scale up of these processes it is necessary to be able to estimate the hydrodynamics and mass transfer performance as a function of column diameter. Many recent experimental studies have emphasised the strong influence of column diameter on bubble column hydrodynamics [1–10]. While there have been several studies of mass transfer in bubble columns [11–16], not a single paper has focussed on the influence of scale.

The main objective of our paper is to investigate the influence of column diameter on the value of the volumetric mass transfer coefficient, $k_La$ and to suggest a scale up strategy for commercial scale reactors. We carried out experiments in columns of three different diameters with the air–water system to study the scale dependence of both the gas hold-up and mass transfer.

## 2. Experimental set-up and procedure

Experiments were carried out in columns of 0.1, 0.15 and 0.38 m in diameter. Air was used as the gas phase. The liquid phase used in the experiments consisted of demineralised water. In all the experiments the initial liquid height was kept constant at 1.6 m. A typical column configuration for the 0.15 m diameter column is shown in Fig. 1. Each column had a 1 mm thick brass plate gas distributor with perforated holes of 0.5 mm diameter on a triangular pitch of 7 mm. In the 0.15 m diameter column a total of 625 holes were drilled; for the 0.38 m diameter column the distributor plate had 2750 holes. The rate of airflow into all columns was regulated by the use of rotameters aligned in parallel, while nitrogen (used as for stripping out the dissolved oxygen) flow was controlled by the use of a manually operated control valve. For the determination of gas holdup, pressure taps were installed along the height of the columns. Two of these taps were connected to pressure ports on a Validyne DP15 pressure transducer, which was in turn coupled to a PC via an analogue to digital converter consisting of the pressure transducer and a voltmeter, as shown in Fig. 1.

To determine the gas holdup, the gas flow rate into the column was adjusted to the desired value using one of the rotameters. Prior to this, the rotameters were calibrated. Sufficient time was given for steady state to be achieved in

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* Corresponding author. Tel.: +31-20-525-7007; fax: +31-20-525-5604.
*E-mail address:* krishna@science.uva.nl (R. Krishna).

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doi:10.1016/S0255-2701(03)00015-1

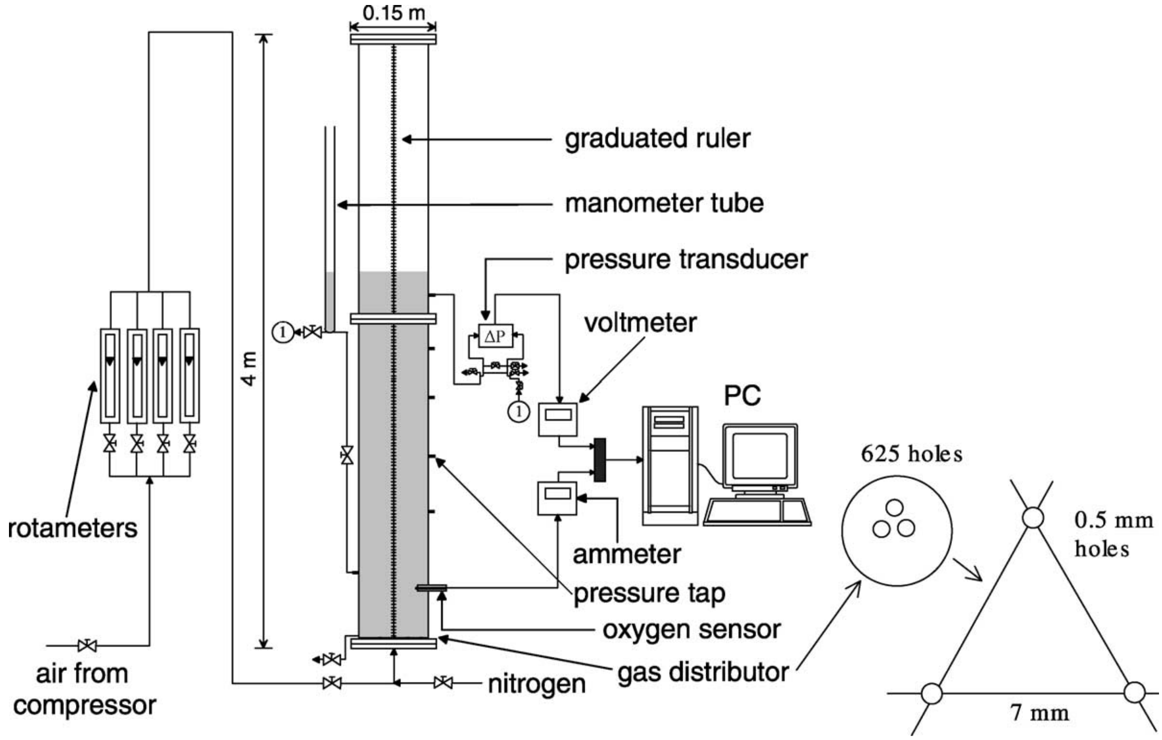
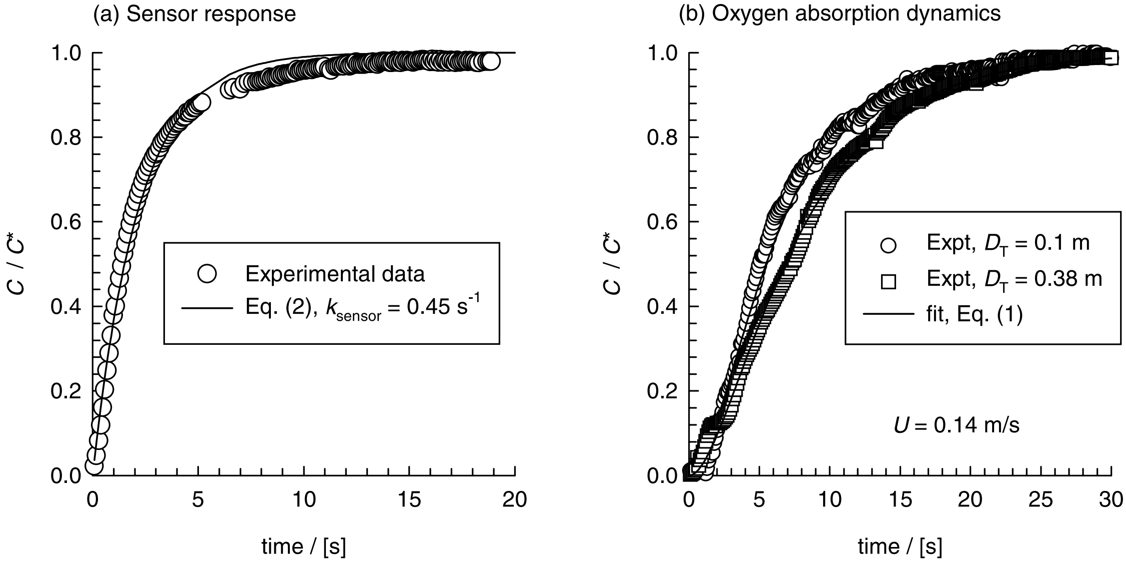


Fig. 1. Typical experimental set-up for the 0.15 m diameter column.

each column after which the increase in liquid pressure at the higher of the two pressure taps used was recorded. This increase occurred due to the presence of gas bubbles in the column, causing the upward displacement of the liquid. The measured pressure signals, obtained in the form of voltage readings were interpreted to obtain information on the gas holdups.

The volumetric mass transfer coefficient $k_La$ was measured by means of the dynamic oxygen absorption method, described in our earlier work [15]. The dissolved oxygen concentration is measured by means of an oxygen electrode (Yellow Springs Incorporated Model 5331), which is connected via an ammeter to an analogue-to-digital converter card located in the PC. The oxygen electrode is placed in the bubble column at a distance of 0.1 m above the gas distributor; see Fig. 1. The application of a 0.13 g ml$^{-1}$ KCl solution between the between the tip of the sensor and an outer membrane, ensured its sensitivity to the presence of oxygen.


(a) Sensor response

(b) Oxygen absorption dynamics

Fig. 2. (a) Dynamic response of oxygen sensor obtained in a glass beaker bubbled with oxygen. (b) Typical oxygen absorption curves for bubble columns of 0.1 and 0.38 m diameters operating at $U = 0.14$ m s$^{-1}$.

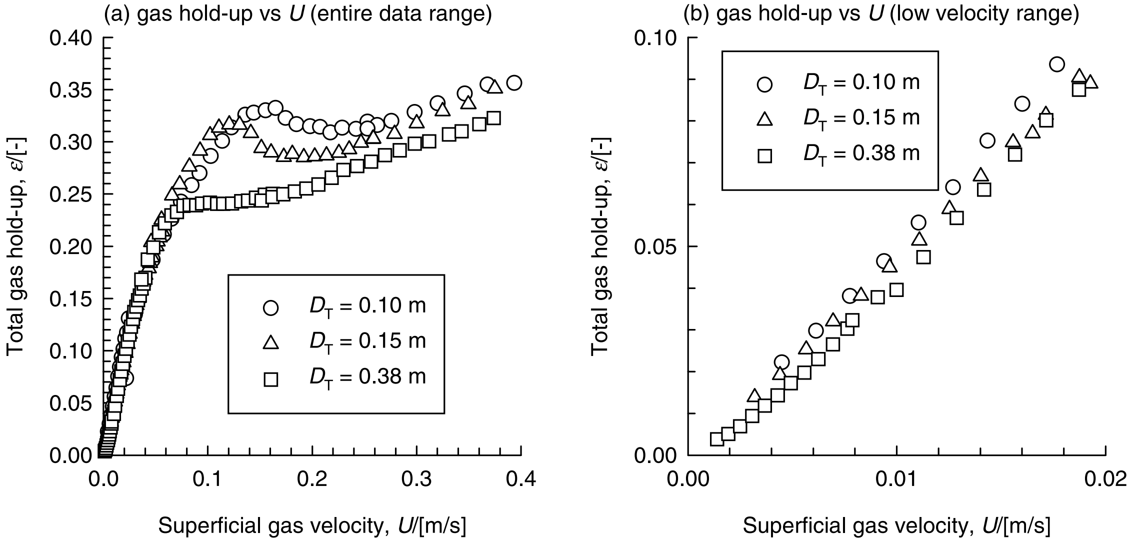


Fig. 3. Gas holdup ε as a function of superficial gas velocity U, obtained in three columns. (a) Entire data set. (b) Focus on the values obtained at low superficial gas velocities.

Firstly, the oxygen was stripped from water almost completely by injection of pure nitrogen through the distributor. When all the oxygen has been stripped out, air was sparged into the column and the oxygen uptake into the liquid phase was monitored continuously by means of the oxygen sensor. The total measurement time was chosen large enough in order to reach the oxygen saturation concentration, $C^*$.

Assuming the liquid phase to be perfectly mixed, the dissolved-oxygen concentration $C$ is described by the relation:

$$\frac{C}{C^*} = 1 - \frac{1}{k_{\text{sensor}} - k_L a_L} \times \left[k_{\text{sensor}}\, e^{-k_L a_L t} - k_L a_L\, e^{-k_{\text{sensor}} t}\right] \quad (1)$$

where $k_L a_L$ is the volumetric mass transfer coefficient per unit volume of *liquid* in the bubble column and $k_{\text{sensor}}$ is the time constant of the oxygen sensor. The time constant of the oxygen sensor was determined before each set of experiments by instantaneously inserting the oxygen electrode in a beaker of water that was saturated with oxygen by the continuous bubbling of oxygen gas into it. Prior to this, the sensor was placed in a beaker of water from which oxygen had been completely stripped off with nitrogen and in which nitrogen was continuously bubbled. A typical dynamic response for the oxygen sensor is shown in Fig. 2 (a). The sensor constant $k_{\text{sensor}}$ was then determined by fitting the response to the relation:

$$\frac{C}{C^*} = 1 - e^{-k_{\text{sensor}} t} \quad (2)$$

In the example shown in Fig. 2 (a), $k_{\text{sensor}} = 0.45\ \text{s}^{-1}$. The membrane surrounding the oxygen electrode was replaced frequently and the sensor constant determined for each membrane. The value of $k_{\text{sensor}}$ was found to vary in the range 0.4–0.46 $\text{s}^{-1}$; this value is significantly higher than the value

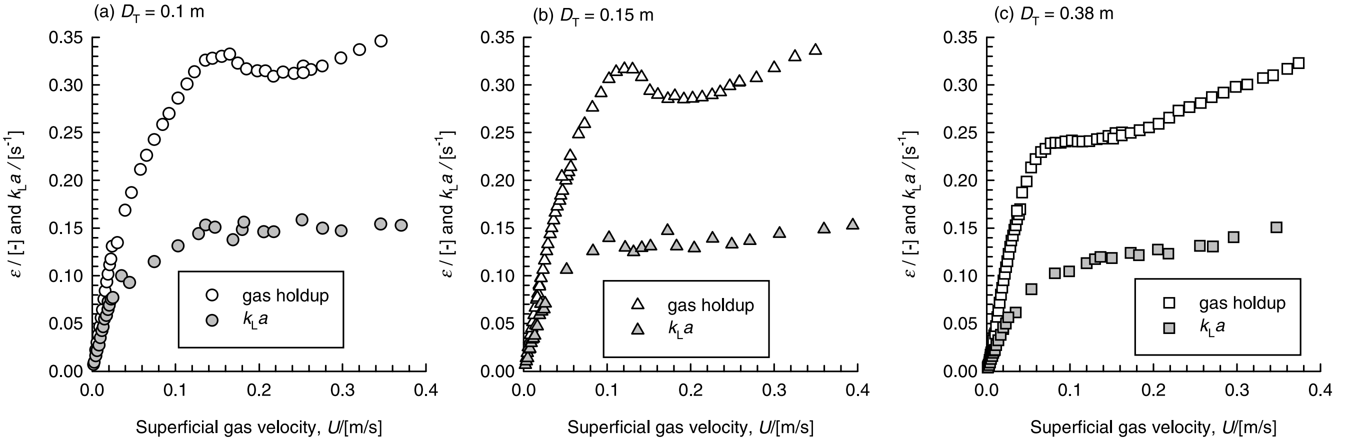


Fig. 4. Variation of gas holdup ε and volumetric mass transfer coefficient $k_L a$ with superficial gas velocity U. (a) 0.10 m column, (b) 0.15 m column, and (c) 0.38 m column.

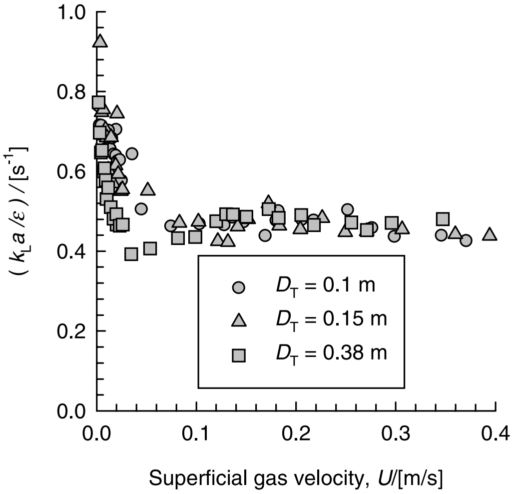


Fig. 5. Variation of $k_L a/\varepsilon$ with superficial gas velocity $U$ for bubble columns of 0.1, 0.15 and 0.38 m diameters.

of $k_L a_L$ determined from the oxygen absorption. Two examples of the oxygen absorption dynamic curves in the bubble columns of 0.1 and 0.38 m, both operating at a superficial gas velocity $U = 0.14$ m s$^{-1}$ are shown in Fig. 2 (b). By fitting these curves to Eq. (1), taking $k_{\mathrm{sensor}} = 0.45$ s$^{-1}$ yields $k_L a_L = 0.223$ and 0.158 s$^{-1}$ for the 0.1 and 0.38 m columns, respectively. The commonly used volumetric mass transfer coefficient per unit volume of (gas+liquid) dispersion, is then calculated from

$$k_L a = k_L a_L (1 - \varepsilon) \tag{3}$$

where $\varepsilon$ is the gas holdup.

## 3. Experimental results for scale influence

The gas holdup $\varepsilon$ is found to decrease slightly with increasing column diameter; see Fig. 3. This decrease in gas hold-up, evident in both the homogeneous (see Fig. 3 (b)) and heterogeneous flow regimes, is due to increased liquid recirculations with increasing column diameter [5,6,9]. In earlier work we had used CFD models to underline the influence of column diameter on gas holdup in both homogeneous [9] and heterogeneous flow regimes [5,6].

The volumetric mass transfer coefficient $k_L a$ follows the same trend as for the gas holdup; see Fig. 4. In Fig. 5 we plot $k_L a/\varepsilon$ as a function of $U$ for the three column diameters. There is no significant dependence of $k_L a/\varepsilon$ on the column diameter for the whole range of $U$ values. For superficial gas velocities below 0.08 m s$^{-1}$, the value of $k_L a/\varepsilon$ drops from a value of 0.8 s$^{-1}$ to a value of 0.5 s$^{-1}$ for all three column diameters. For $U > 0.08$ m s$^{-1}$, $k_L a/\varepsilon$ is practically independent of gas velocity and column diameter $D_T$; the value of this parameter is found to be about 0.48 s$^{-1}$. The physical significance of the parameter $k_L a/\varepsilon$ is that it represents the volumetric mass transfer coefficient per unit volume of bubbles. One interpretation of the constancy of $k_L a/\varepsilon$ is that the effective bubble diameter $d_b$ is independent of the gas velocity. Vermeer and Krishna [16] were the first to point out the constancy of $k_L a/\varepsilon$ in the heterogeneous flow regime. However, the constancy of the effective bubble diameter $d_b$ in the heterogeneous flow regime can be rationalised only if we take account of the fact that frequent coalescence and breakup of the "large" bubbles causes the effective bubble diameter to be maintained at a low, constant, value; this conclusion was reached earlier by De Swart et al. [17] on the basis of video imaging experiments in a 2D slurry bubble column.

## 4. Re-analysis of experimental data of Jordan and Schumpe [13]

Jordan and Schumpe [13] have studied mass transfer coefficients at various gas densities in the range 0.19–47 kg m$^{-3}$ using a bubble column of 0.1 m diameter. We have re-analysed their set of experimental data using 1-butanol as the liquid phase. Both gas holdup $\varepsilon$ and $k_L a_L$ are found to increase significantly with increased gas densities; see Fig. 6

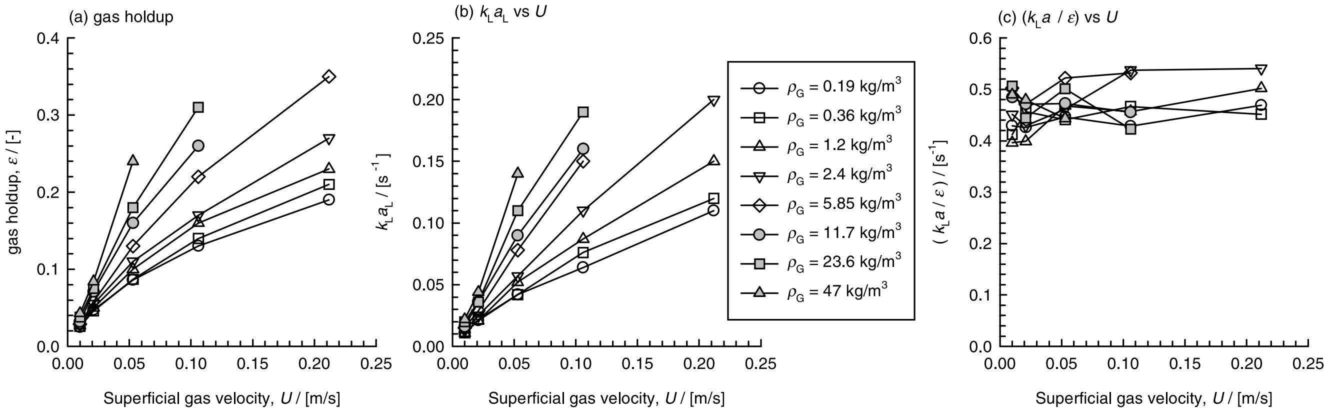


Fig. 6. Gas holdup and mass transfer data of Jordan and Schumpe [13] obtained in a 0.1 m diameter column with 1-butanol as the liquid phase. (a) Variation of gas holdup $\varepsilon$ with superficial gas velocity $U$. (b) Variation of $k_L a_L$ with $U$. (c) Variation of $k_L a/\varepsilon$ with $U$.

(a) and (b). This result is in agreement with the work of Letzel et al. [15]. From the data of Jordan and Schumpe [13] we have calculated $(k_L a/\varepsilon) = k_L a_L (1-\varepsilon)/\varepsilon$; the data have been plotted in Fig. 6 (c). We note that $(k_L a/\varepsilon)$ is practically independent of the gas velocity *U and* gas density; the value of this parameter is found to be around 0.45 $s^{-1}$, slightly lower than the value 0.48 $s^{-1}$ found in our experiments. This lower value could be due to the lower diffusivity of oxygen in 1-butanol than in water. This result also seems to agree with the those obtained by Letzel et al. [15], at varying system pressures.

## 5. Conclusions

We have measured the gas holdup, $\varepsilon$, and volumetric mass transfer coefficient, $k_L a$, for the air–water system in columns of three different diameters, $D_T = 0.1$, 0.15 and 0.38 m. Both $\varepsilon$ and $k_L a$ show similar trends with varying $U$ and $D_T$. An interesting, and important, finding of this work is that, for $U > 0.08$ m $s^{-1}$, the value of $k_L a/\varepsilon$ was found to be practically independent of column diameter *and* superficial gas velocity $U$. The experimental data of Jordan and Schumpe [13] also show that $k_L a/\varepsilon$ is also independent of gas density. The findings of the work reported our paper provide a useful scale up rule for estimating the mass transfer coefficients for bubble columns of large diameter, operated at high gas velocities at elevated pressures.

## Appendix A. Nomenclature

| | |
|---|---|
| $a_L$ | gas–liquid interfacial area per unit liquid volume ($m^{-1}$) |
| $a$ | gas–liquid interfacial area per unit (gas+liquid) dispersion volume ($m^{-1}$) |
| $d_b$ | diameter of bubble (m) |
| C | oxygen concentration in the liquid phase (arbitrary units) |
| $C^*$ | saturation concentration of oxygen in liquid (arbitrary units) |
| $D_T$ | column diameter (m) |
| $k_L$ | liquid-side mass transfer coefficient (m $s^{-1}$) |
| $k_{sensor}$ | sensor response constant ($s^{-1}$) |
| $t$ | time (s) |
| $U$ | superficial gas velocity (m $s^{-1}$) |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | total gas hold-up (dimensionless) |
| $\rho_G$ | gas density (kg $m^{-3}$) |

*Subscripts*

| | |
|---|---|
| b | referring to bubbles |
| L | referring to liquid |
| T | tower or column |

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