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POSTER COMMUNICATION

Improvement of baffle type Rotating Packed Bed's packing by visual study

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Abstract
Process intensification is one of the key branches of process engineering. High gravity equipment achieves intensification by substituting gravity with much higher centrifugal force. Rotating Packed Bed is the leading example of high gravity solutions, strongly facilitating gas-liquid mass transfer. However, cylindrical packings come with certain drawbacks, such as dry spots, that can be overcome with new solutions, such as baffle-based packing geometries. However, when baffles are arranged too close to each other, liquid bridges are formed between them, which may lead to decrease in mass transfer efficiency. This work is concerned with improvement of a Zickzack-like internal by the means of visual studies with the use of high-speed camera. According to measured ligament break-up length, two new packings were designed for particular rotational speeds and tested experimentally for effective mass transfer area and wet pressure drop.

Keywords
hydrodynamics, visual study, Rotating Packed Bed, packing, mass transfer area

1. INTRODUCTION

Rotating Packed Bed (RPB) is a novel apparatus for contacting two phases of different densities, e.g. liquid and gas or liquid and vapor, where the gravitational force is substituted with much higher centrifugal force (Ramshaw and Mallinson, 1981). The main part of an RPB unit is a rotating packing, responsible for developing high mass transfer area and providing intense micro-mixing of the phases. A schematic representation of a counter-current RPB unit is shown in Figure 1. The most commonly used packing types for RPBs include wire mesh (Jassim et al., 2007) or metal foam (Zheng et al., 2016). However, such porous packings often pose drawbacks, such as high pressure drop and limited operational window, as well as dry zones due to radial direction of centrifugal acceleration (Groß et al., 2019). These drawbacks can be overcome with the use of structural packings.

The first example of a structural RPB packing was presented by Qammar et al. (2019). The *Zickzack* internal, inspired by the rotating zigzag bed apparatus (Wang et al., 2008) is made of two solid plates with alternating, concentrically arranged baffles, each equipped with an additional weir to provide higher liquid holdup. Recently, Zawadzki et al. (2023) used computational fluid dynamics for optimization of the baffle shape for RPB structural internals in order to minimize the pressure drop. The optimization allowed to decrease the pressure drop by 50%, while increasing the effective mass transfer area by up to 30% in comparison with the original *Zickzack*.

Although the shape and inclination angle of the baffles have been successfully optimized, the packing still leaves room for optimization. In particular, baffle spacing inside the packing is also key to its performance, as too dense arrangement may create very high flow resistance, while too spaced baffles may decrease the mass transfer efficiency due to limited micro-mixing. In this work, visual studies have been used to optimize baffle spacing, based on ligament breakup distance at varying liquid flow rates, baffle radii and rotational speeds.

2. MATERIALS AND METHODS

2.1. Visual study of hydrodynamics

The measurement of ligament break-up was visualised using high-speed camera in a transparent RPB at Brno University of Technology. Despite the fact that the original packing (see Figure 5a) was manufactured with the use of a transparent resin, the unevenness of the printed surfaces did not allow to make quantitative measurements of the liquid ligaments. It was therefore necessary to simplify the packing. Hence, four rotors of various diameters were manufactured with only one baffle placed on the outer diameter. A pressure swirl atomizer discharged a continuous liquid sheet to ensure uniform liquid distribution on the packing's internal part.

A high-speed camera FASTCAM SA-Z (Photron, Japan), equipped with a long-distance microscope 12X Zoom lens (NAVITAR, New York, USA), was used for backlight recordings. The lens was composed of a 2X F-mount adapter (type 1-62922), a 12 mm F.F zoom lens (type 1-50486) together with 0.25X lens (type 1-50011). A continuous LED light model HPL3-36DD18B (Lightspeed Technologies, USA) illuminated the recorded area of 1024 × 1024 px with a spatial resolution of 18 μm/px. A shutter speed for all recordings was equal to 3.75 μs.

The obtained recordings showed formation of ligaments on the baffles, as well as their breakup into droplets, as shown in Figure 3. This figure also presents the methodology of ligament length analysis. Ligament length was defined as the maximum length the ligament can spread before it breaks up into droplets. The magnitude of ligament length was determined using dimensions in the x and y directions. Approximately, 20–30 ligaments were measured for each experimental point to determine the average value and standard deviation.

2.2. Measurement of effective mass transfer area and wet pressure drop

The measurements of wet pressure drop and effective mass transfer area were performed on the RPB device owned by Lodz University of Technology. The experimental rig was equipped with a liquid pump, an air blower, air humidifier, a battery of compressed CO_2 bottles, three CO_2 infrared measurement devices (sampling from inlet, outlet, and inside the RPB casing), a hydraulic lock, and a differential pressure gauge for measuring pressure drop between the inlet and the outlet of the RPB.

The reaction system consisted of 0.2 mol.% CO_2 in air, and 1M NaOH solution. This system was chosen because it fulfils the requirements of the methodology of direct mass transfer area calculation posed by Charpentier (1981). With this method, the a_{eff} can be determined with Equation (1).

$$a_{\text{eff}} = \frac{\Phi}{\left(k_r \cdot D_{\text{CO}_2} \cdot {C^*_{\text{CO}_2|\text{avg}}}^2 \cdot C_{\text{NaOH}}\right)^{0.5}} \tag{1}$$

The experimental determination of the effective mass transfer area and wet pressure drop was conducted under the gas flow of 20 m^3/h, with three liquid flow rates of 45, 90, 180 L/h, and at four different rotational speeds of 300, 600, 900 and 1200 rpm.

3. RESULTS AND DISCUSSION

3.1. Visual study

The purpose of the visual study was to determine liquid ligament breakup length at varying liquid flow rates, baffle radii, and rotational speeds. A previously prepared transparent baffle packing (Figure 5a) was first investigated with the fast camera, and liquid bridges could be observed between the baffles (see Figure 2). However, the assembled packing was too opaque to make quantitative measurements. Thus, single baffle packings were installed in the RPB and the liquid structures were observed at their outer rim. An exemplary photo of ligaments forming at the baffle is presented in Figure 3.

It was observed that liquid flow rate did not influence ligament geometry, as its increase only led to increased amount of formed ligaments. However, the rotational speed and baffle radius had a significant effect on ligament length, as it turned out to be a function of the angular velocity of the liquid at the baffle. The fitting of the function and its equation are presented in Figure 4.

3.2. Investigation of tailored packings

With the knowledge from the results described in Section 3.1, two packings were made specifically for the desired rotational speeds: 600 rpm ("600", Figure 5b) and 1200 rpm ("1200", Figure 5c). The distances between the baffles were dictated by the ligament breakup length modeled by the function shown in Figure 4, thus preventing formation of liquid bridges between subsequent baffles at the desired rotational speeds. As lower rotational speeds correspond to longer ligaments, the tailored packing for 600 rpm is characterized by larger distances between baffles. In all cases, the distances decrease quadratically with the radius. Thus, the packings tailored for 600 rpm and 1200 rpm have different numbers of baffles.

The results of the mass transfer measurements are presented in Figure 6a. It can be seen that the tailored packings do not show strong increases in efficiency at their desired rotational speeds. In all cases, including the initial packing, the mass transfer area increases steadily with the rotational speed, except for the cases at 300 rpm, where the Initial and 1200 packings operate under conditions close to flooding, which causes sudden spikes in effective mass transfer area. It can be also seen that within the 600–1200 rpm range, the Initial packing and the 1200 packing behave very similarly, while the effective mass transfer areas generated by packing 600 are significantly lower.

The increasing number of baffles forces the phases to flow through narrower channels, thus increasing the flow resistances. In Figure 6b wet pressure drops of the three packings are shown as functions of rotational speed. With the exception of 1200 packing operating at 300 rpm (flooding), very steady trends can be seen for all three packings. Both rotational speed and number of baffles have positive effect on the wet pressure drop.

4. CONCLUSIONS

With the assumption that the design of the packings prevents liquid bridge formation at particular rotational speeds, and given the data shown in Figure 6, it can be concluded that liquid bridges are not the limiting factor of the mass transfer area in the baffle-type structural packing. It is therefore possible that liquid films forming at the solid elements of the packing contribute to the mass transfer efficiency more significantly than the free liquid structures between the baffles. From the experimental data it can be seen that increase in the number of baffles leads to increase in mass transfer area as well as pressure drop, and tightly arranged baffles increase the risk of flooding at low rotational speeds. In future work, gas flow may also be taken into account for visual studies, as it may also influence the formation of liquid structures within the packing.

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SYMBOLS

a_{eff} effective mass transfer area, m^2/m^3
D diffusivity, m^2/s
C molar concentration, $kmol/m^3$
k_r reaction rate constant, 1/s

Greek letters

Φ absorption rate, kmol/s

Superscripts

$*$ gas-liquid equilibrium

Subscripts

avg average between casing and outlet
CO_2 carbon dioxide
NaOH sodium hydroxide

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Improvement of Baffle Type Rotating Packed Bed's Packing by Visual Study

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Introduction

Rotating Packed Bed (RPB) is a gas-liquid or vapor-liquid contact apparatus, where gravity force is replaced by centrifugal force [1]. The main part of the RPB unit is a rotating packing, which is responsible for increasing mass transfer performance. Nowadays, different types of packing are used, e.g. wire mesh, metal foam, baffle packing [2]. One of the most promising ones is the Zickzack packing invented by Qammar et al. [3] and improved by Loll et al. [4]. The aim of this research is to investigate hydrodynamics inside Zickzack-type packing via combination of visual study and mass transfer experiments.

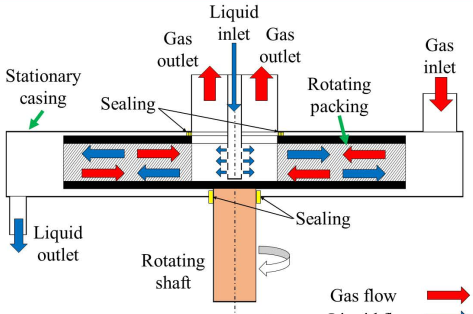


Figure 1. RPB sheme

Materials and Methods

Liquid ligament breakup distance was measured via visual study using a high-speed camera FASTCAM SA-Z type 2100K-M-16GB at Brno University of Technology.

Developed and manufactured packings and experimental investigation of wet pressure drop and effective mass transfer area have been done at the Lodz University of Technology.

Effective mass transfer area was measured using diluted CO_2 (0.2%vol) and concentrated (1M) NaOH water solution. In presented conditions mass transfer process is limited only by effective mass transfer area.

Visual study

During the hydrodynamics investigation, liquid bridges were observed (**Figure 2**). Because of surface tension, the liquid uses the Bridges as a „highway" connecting subsequent baffles, which decreases the potential mass transfer area.

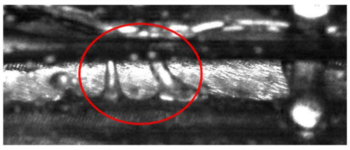


Figure 2. Fast-cam picture with marked liquid bridges

Bridges appear only under specific conditions. The aim of the research was to find conditions under which the bridges would not form. In this case, the liquid ligament breakup distance was measured on a single baffle (**Figure 3**).

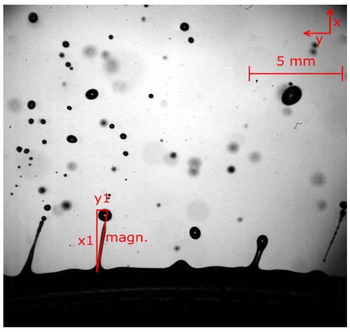


Figure 3. Ligament breakup distance measurement

Experimental conditions:

- four geometries: 73, 100, 150, 200 mm
- three liquid flowrates: 45, 90, 121 $kg \cdot h^{-1}$
- six rotational speeds: 397, 560, 790, 960, 1115 rpm

The visual study results are shown in **Figure 4**. The value of the quotient of ligament length and baffle edge length as a function of angular velocity and baffle radius is independent of liquid flowrate.

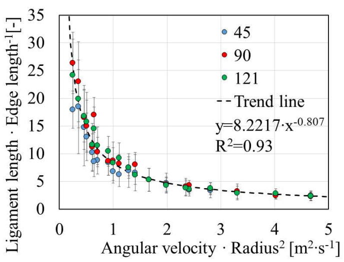


Figure 4. Ligament length in function of massless angular momentum

The larger the value on the X-axis, the more repeatable the results.

Tailored packings

Using the equation shown in **Figure 4** two new packing geometries were tailored to:

- 600 rpm (called **600**)
- 1200 rpm (called **1200**).

Obtained packing geometries (**Figure 5**) were tested experimentally for wet pressure drop and effective mass transfer area (**Figure 6**). A minor influence of the liquid flow rate on the results obtained was observed

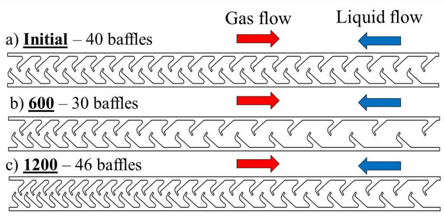
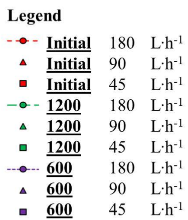


Figure 5. Investigated packings cross-sections



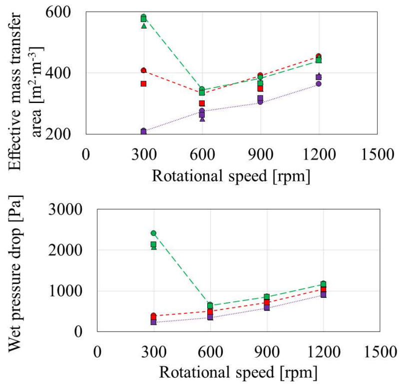


Figure 6. a) Effective mass transfer area; b) Wet pressure drop in function of rotational speed

Conclusions

- Increasing the number of baffles increased both the wet pressure drop and the effective mass transfer area.
- The hypothesis that ligament breakup distance is a function of centrifugal acceleration has not been confirmed, and adjusting the packing geometries to the set rotational speeds did not lead to the expected results.
- In the future, the gas flow should be taken into account when testing ligament breakup distance, as it can have a significant impact on the obtained results.

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