Characterization of the Operating Limits of a Two-Rotor Rotating Packed Bed

Tobias Pyka [a, b, *], Katharina Kohl [a], Jörg Koop [b], Christoph Held [a], Gerhard Schembecker [b]

[a] TU Dortmund University, Department of Biochemical and Chemical Engineering, Laboratory of Fluid Separations, Emil-Figge-Straße 70, 44227 Dortmund, Germany

[b] TU Dortmund University, Department of Biochemical and Chemical Engineering, Laboratory of Plant and Process Design, Emil-Figge-Straße 70, 44227 Dortmund, Germany

*tobias.pyka@tu-dortmund.de

Abstract. The use of rotating packed beds (RPBs) is a promising way to intensify distillation processes and to reduce equipment size. This kind of high gravity equipment exploits an adjustable centrifugal force instead of the constant earth's gravitational field to enhance the mass transfer by generating a high mass transfer area.

In this work, a two-rotor RPB (2R-RPB) is characterized regarding its operating limits at rotational speeds (n_{rot}) of up to 1200 min^{-1}, F-factors (F_G) of up to 4.9 Pa$^{0.5}$, and liquid loads (LL) of up to 54.6 m^{3}m^{-2}h^{-1}. A special focus is on the wet pressure drop within each rotor. Knowledge about the operating limits of a multi-rotor design is crucial for a distillation process and gives insights into the maximum fluid loads and wet pressure drop at certain n_{rot}. The study revealed an equal contribution of the rotors regarding the wet pressure drop.

Keywords two-rotor rotating packed bed, wet pressure drop, operating limits, F-factor, liquid load, flooding

1. Introduction

The operating limit, i.e. the maximum F_G and LL in countercurrent, of conventional columns, is restricted by gravity. Furthermore, the maximum LL and F_G depend mutually on each other. Most conventional columns cannot be operated at F_G above 3 Pa$^{0.5}$ and LL above 20 m^{3}m^{-2}h^{-1} at the same time, and additionally with packings offering high specific surface area [1]. High gravity equipment like RPBs can overcome the capacity limitations in a compact design by applying a centrifugal field [2]. Unfortunately, increasing the separation performance of one-rotor RPBs (1R-RPBs) by increasing the packing diameter proved to be a challenging task [3–6].

A way to overcome the limited separation performance of 1R-RPBs is a multi-rotor design with multiple rotors installed coaxially on a single shaft [7, 8]. Whereas the operating limits of 1R-RPB are well understood, the operating limits of 2R-RPBs are nearly unexplored [9]. The flow of the fluids in countercurrent operating is as follows: The gas is fed at the bottom of the casing and flows consecutively through the lower rotor, intermediate floor, and upper rotor (see Fig. 1).

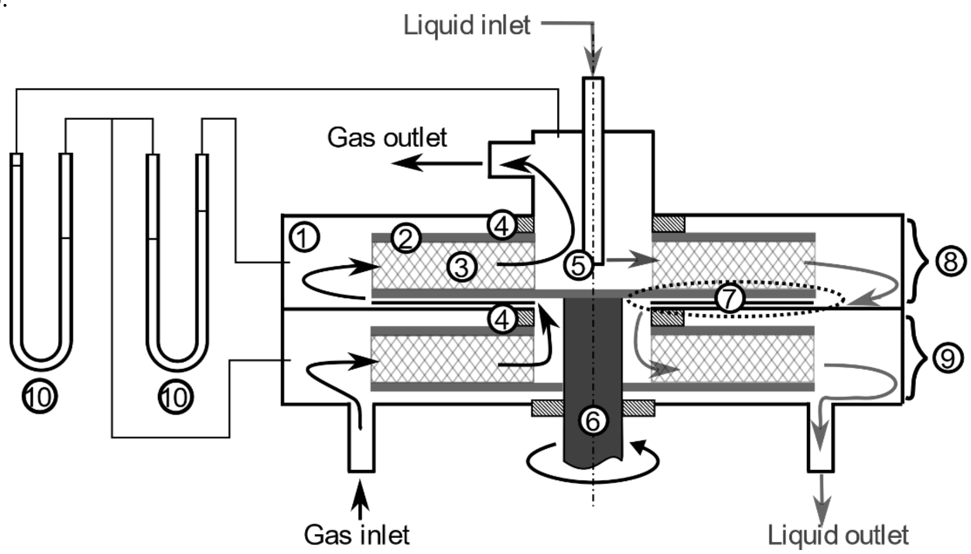

Fig. 1 Schematic of a 2R-RPB and its periphery. (1) Casing, (2) rotor plates, (3) annular-shaped packing, (4) floating ring seal, (5) liquid distributor, (6) shaft, (7) intermediate floor, (8) upper rotor, (9) lower rotor, and (10) u-tube.

In the upper rotor, the liquid is introduced by nozzles and passes the packing. After that, it is collected by the intermediate floor, flows to the eye of the lower rotor by gravity, and is introduced to the packing solely by centrifugal force. Therefore, the following question arises: How does the kind of liquid distribution within each rotor impact the operating limits? Knowledge about the operating limits of the 2R-RPB is crucial for the design of any gas-liquid contacting process and gives insights into the maximum fluid loads and wet pressure drop at certain n_{rot}. To evaluate the hydrodynamic behavior of each rotor separately a systematic procedure was developed to simulate distillation under total reflux.

2. Theoretical background

In conventional columns, the operating limits are characterized by the flooding limit. At the flooding limit, the countercurrent gas flow prevents the liquid from flowing down and the liquid hold-up increases strongly leading to an unstable operating behavior [10]. This kind of liquid accumulation also occurs close to the inner side of the packing, the so-called eye of the RPB, where the lowest centrifugal force acts on the liquid. The following parameters were used to express the fluid loads and characterize the operating limits:
LL is defined by the ratio of the liquid volume flow $\dot{V}_L$ and the cross-sectional area A_c (eq 1) [9].

$$LL = \frac{\dot{V}_L}{A_c} \qquad (1)$$

F_G is a measure of the capacity of the gas flow in the rotor (eq 2) [9].

$$F_G = \frac{\dot{V}_G}{A_c}\sqrt{\rho_G} = w_G\sqrt{\rho_G} \qquad (2)$$

$\dot{V}_G$, ρ_G, and w_G denote the gas volume flow, the density of the gas, and the gas velocity. In RPBs it is common to use the inner cross-sectional area of the packing as A_c since the highest LL and F_G are present there and flooding initiates at that point [9].
The operating limits of RPBs can be determined by observing the gas outlet, quantifying the liquid hold-up by computed tomography, or measuring the pressure drop between the gas inlet and outlet [9, 11, 12]. While entrainment of liquid droplets is hard to quantify by a visional observation of the gas outlet, the use of computed tomography requires high-cost equipment [9, 12].
Measurement of the wet pressure drop is easy to perform and inexpensive to implement. The three most common definitions in the literature of the operating limits determined by pressure drop are namely of Rajan et al. [13], Singh et al. [11], and Lockett [14]. Fig. 2 shows a schematic of a typical pressure drop curve at constant fluid loads and varied n_{rot} and the different definitions are indicated.

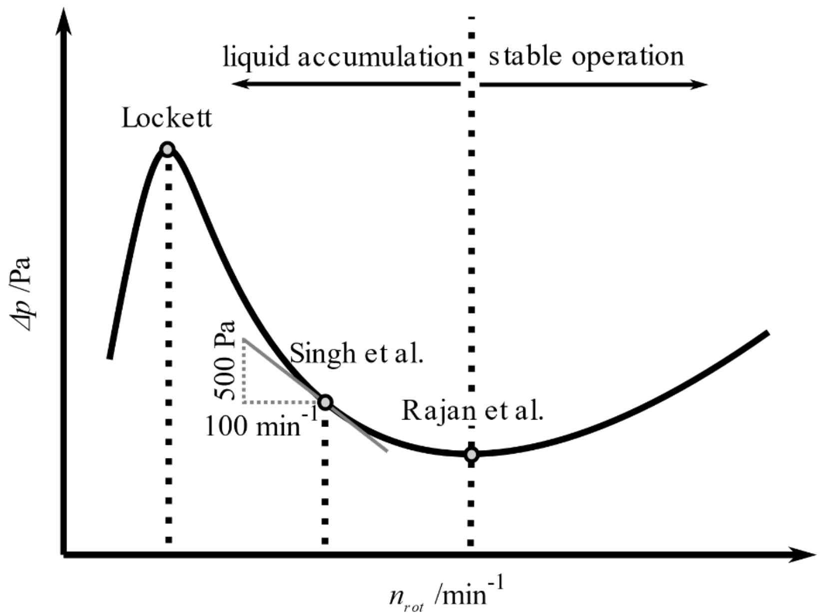

Fig. 2 Sketch of a characteristic wet pressure drop curve for an RPB including definitions of minimum n_{rot} by Lockett [14], Singh et al. [11], and Rajan et al. [13].

At high n_{rot}, a stable process is achieved and the elevated pressure drop is mainly caused by the high n_{rot}. By decreasing the n_{rot} also the pressure drop decreases and is passing through a pressure drop minimum which Rajan et al. [13] defined as the minimum n_{rot} regarding the operating limit. After that, the pressure increases due to the accumulation of liquid in the eye of the rotor [15]. The definition of the minimum n_{rot} of Singh et al. [11] is located at the slope of the pressure drop curve of 500 Pa/100 min^{-1}. Further decrease of the n_{rot} leads to a pressure drop maximum at which the liquid is entrained by the gas. This maximum represents the minimum n_{rot} by Lockett [14].

3. Material and methods

In this study, a 2R-RPB equipped with two rotors of identical dimensions (d_o = 600 mm, d_i = 165 mm, and h = 10 mm) was investigated. Each rotor was equipped with a metal foam packing (NCX1116, Recemat BV, Dodewaard, Netherlands) with a specific surface area of 1000 m^2 m^{-3} and a porosity of 0.92. At the inner circumference of each packing is a ring with cutouts installed to space the rotor plates, which is called eye ring. By-passing of the gas between the lower rotor and intermediate floor as well as between the upper rotor plate and the casing wall was prevented by the use of a floating ring seal (see Fig. 1). The intermediate floor consists of a lower and an upper plate with an axial distance of 10 mm from each other, which is realized by six equidistant cross struts. The upper plate shields the liquid from the influence of the rotor. Thus, circular liquid flows on the intermediate floor are less likely and accumulation of liquid due to centrifugal forces were avoided. The liquid flowing from the intermediate floor is collected at the top of the eye ring of the lower rotor. The collected liquid is then flowing through six axial holes in the eye ring through it and then into the packing. That arrangement ensured liquid redistribution and even wetting of the lower packing in the circumferential direction. To measure the pressure drop of the lower rotor and of the entire 2R-RPB, two u-tubes were used (accuracy $\pm$ 10 Pa). One u-tube was connected at the bottom of the casing and the outer top casing and the other was connected at the bottom of the casing and the eye of the upper rotor (see Fig. 1). The gas flow of air at ambient conditions was measured by a rotameter KFR-535300 from KOBOLD Messing GmbH (Hofheim/Ts., Germany, accuracy: $\pm$2% of full scale) and the liquid flow of water at ambient conditions was measured by an electromagnetic flow meter FMG92-PVDF-BSP from OMEGA Engineering GmbH (Deckenpfronn, Germany, accuracy $\pm$1% of full scale).
To investigate the operating limits of the corresponding LL and F_G were set at a n_{rot} of 1200 min^{-1}, then the n_{rot} was decreased stepwise until no stable operating was feasible. The maximum values of F_G and LL were 4.9 Pa$^{0.5}$ and 54.6 m^{3}m^{-2}h^{-1} respectively. The parameter sets were chosen to enable an estimation of the hydraulic operating behavior during distillation experiments under total reflux using the test system cyclohexane/n-heptane. The procedure was as follows: First, F_G was set. We assumed that the vapor volume flow of F_G is completely condensed and returned to the

2R-RPB. To obtain the corresponding LL of F_G of n-heptane, we used the vapor density and the liquid density of n-heptane for the calculation of LL. This implies a proportionality between LL and F_G.This was done to simulate the hydraulic behavior of the distillation of the system cyclohexane/n-heptane under total reflux at ambient pressure. We are aware of the fact that the physical properties of liquid n-heptane or cyclohexane like contact angle, surface tension, and wetting behavior are different from water, and these properties affect hydrodynamics inside the packing. However, we use the experiments for general characterization of the RPB's hydraulics as well as estimation of the pressure drop and operating behavior during distillation. Every parameter set was measured twice and all standard deviations calculated were smaller than the accuracy of the u-tubes.

4. Results and discussion

Figure 3 shows the wet pressure drop over the n_{rot} of the entire RPB and the lower rotor at different fluid loads.

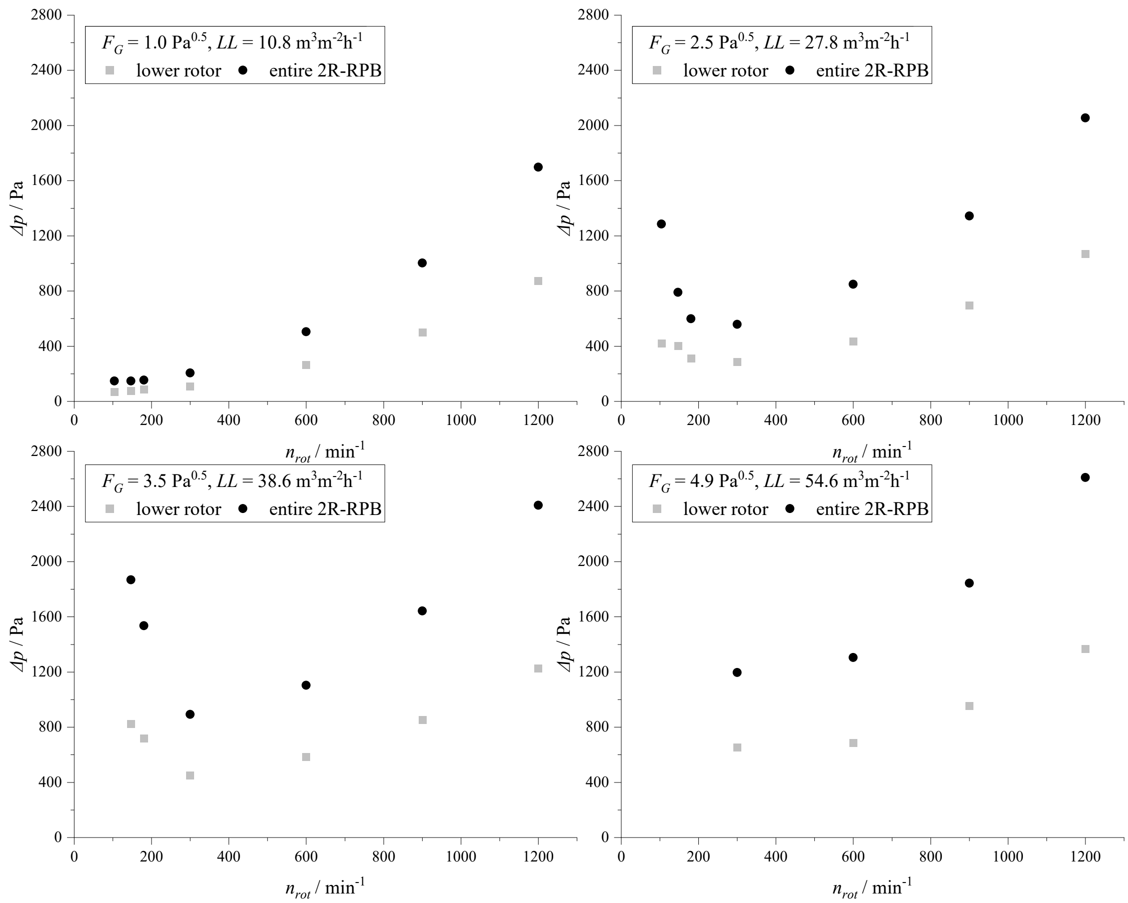

Fig. 3 Wet pressure drop at different n_{rot}, F_G and LL of the lower rotor of 2R-RPB and the entire 2R-RPB.

The wet pressure drop curve is showing a typical course with a minimum for F_G higher than 1.0 Pa$^{0.5}$. The reason for the increase of pressure drop at low n_{rot} is that the liquid is accumulating at the eye of the rotor, hence reducing the effective cross-sectional area for the gas flow. Eventually, at the maximum pressure drop at low n_{rot}, the gas entrains the liquid. At higher n_{rot}, the accumulation of liquid is avoided by the increased radial acceleration. The increase of the pressure drop at high n_{rot} is mainly caused by the rotation of the packing. The decreased porosity of the wetted packing has a minor influence on the wet pressure drop since the liquid hold-up is decreasing at a high n_{rot} [12].
While at F_G of 1.0 Pa$^{0.5}$ and LL of 10.8 m^{3}m^{-2}h^{-1} the operation was not restricted by the n_{rot} investigated, at F_G of 4.9 Pa$^{0.5}$ and LL of 54.6 m^{3}m^{-2}h^{-1} a n_{rot} of 300 min^{-1} was required for stable operating. Thus, the operating limits at high fluid loads are shifting toward higher n_{rot}. Bornhütter [16] determined the operating limits for a conventional column with the same operating conditions (air/water, T = 293 K) which was equipped with Hiflow-Ring 50 mm PP

with a similar porosity as the metal foam of 0.93. Flooding was reached at $F_G = 3$ Pa$^{0.5}$ and $LL = 40$ m^{3}m^{-2}h^{-1}. Comparing it with F_G of 4.9 Pa$^{0.5}$ and LL of 54.6 m^{3}m^{-2}h^{-1} a capacity increase of 63 % was enabled by using the RPB. It is worth noting that at F_G of 4.9 Pa$^{0.5}$ and LL of 54.6 m^3 m^{-2} h^{-1} no flooding occurred above n_{rot} of 300 min^{-1} which indicates the feasibility to further increase F_G and LL by increasing n_{rot}.
Our preliminary work demonstrated that the dry pressure drop of the upper and lower rotor of the apparatus was the same. This behavior can be also observed at the wet pressure drop, at least for most of the investigated conditions (F_G, LL, n_{rot}). At the lowest n_{rot} enabling stable operating for F_G of 1.0 Pa$^{0.5}$, 2.5 Pa$^{0.5}$, and 3.5 Pa$^{0.5}$ the wet pressure drop of the upper rotor is significantly higher than that of the lower rotor. The only constructional difference between the lower and the upper rotor is the liquid distribution. While in the upper rotor the liquid is sprayed on the packing via nozzles, at the lower rotor no nozzles are installed. Equal liquid distribution results in an increased wetting of the packing which leads to an increased liquid hold-up. This in turn reduces the cross-sectional area for the gas flow resulting in an increased pressure drop. Thus, the pressure drop of the upper rotor is higher than the lower rotor since the nozzles distribute the liquid more equally within the packing than without nozzles. The increased wet pressure drop of the upper rotor is not present at $n_{rot} \geq 180$ min^{-1}. One possible explanation is that the higher n_{rot} improves the axial liquid distribution at the lower rotor. Therefore the impact of a different kind of liquid distribution at the upper and lower rotor diminishes at higher n_{rot} and both rotors contribute equally to the wet pressure drop. Luo et al. [8] expected an additional pressure drop due to the liquid flow at the intermediate floor this could not be confirmed by this study. The impact of the intermediate floor on the wet pressure can be for the investigated parameter sets neglected. This is an indicator for a linear increase of the wet pressure drop with the number of rotors in RPBs.

5. Conclusion

In this study, the operating limits of a 2R-RPB were characterized at F_G up to 4.9 Pa$^{0.5}$ and at LL up to 54.6 m^{3}m^{-2}h^{-1}. At all F_G and LL investigated a stable operation was possible representing a capacity increase compared to conventional columns. Furthermore, at the lowest n_{rot} of each fluid load except F_G of 4.9 Pa$^{0.5}$ and LL of 54.6 m^{3}m^{-2}h^{-1} an increased wet pressure drop of the upper rotor could be observed which indicates an axial maldistribution of the liquid at the lower rotor. Despite the difference in the wet pressure drop at low n_{rot}, the upper and the lower rotor contribute equally to the wet pressure drop while the intermediate floor can be neglected. Therefore the different kinds of liquid distribution at the lower and the upper rotor do not impact the wet pressure drop, which does not necessarily mean that the hydrodynamic behavior within both rotors is the same. Furthermore, the intermediate floor does not restrict the operating limits which enable the operating with more than two rotors by inserting additional intermediate floors.
To get deeper insights into the hydrodynamic behavior caused by different kinds of liquid distribution, visual methods like computed tomography are necessary. The focus on the influence of different kinds of liquid distribution should lay on quantifying the liquid hold-up and the axial liquid distribution to overcome liquid maldistribution to increase the separation performance. Since the feasible operating range of the 2R-RPB was determined, in the next step the optimal operating conditions regarding n_{rot} and fluid loads with mass transfer experiments need to be conducted. In addition, the mass transfer experiments could reveal the impact of the different kinds of liquid distribution since a liquid maldistribution may lead to a loss of separation performance.

Nomenclature

Latin letters

A_c	cross sectional area	m^2
d_i	inner diameter of rotor	mm
d_o	outer diameter of rotor	mm
F_G	F-factor	Pa$^{0.5}$
h	height of rotor	mm
LL	liquid load	m^3 m^{-2} h^{-1}
n_{rot}	rotational speed	min^{-1}
p	total pressure	Pa
$\dot{V}_G$	gas volume flow	m^3 h^{-1}
$\dot{V}_L$	liquid volume flow	m^3 h^{-1}
w_G	gas velocity	m s^{-1}

Greek letters

Δ	difference	-
ρ_G	density of gas	kg m^{-3}

References

1. Yildirim Ö, Flechsig S, Brinkmann U, Kenig EY. Bestimmung der Lastgrenzen konventioneller Strukturpackungen und Anstaupackungen mithilfe des Wallis-Plots. Chemie Ingenieur Technik 2015; 87(10): 1348–56.
2. Rao DP, Bhowal A, Goswami PS. Process Intensification in Rotating Packed Beds (HIGEE): An Appraisal. Ind. Eng. Chem. Res. 2004; 43(4): 1150–62.
3. Cortes Garcia GE, van der Schaaf J, Kiss AA. A review on process intensification in HiGee distillation. J. Chem. Technol. Biotechnol 2017; 92(6): 1136–56.
4. Chen Y-S, Lin C-C, Liu H-S. Mass Transfer in a Rotating Packed Bed with Various Radii of the Bed. Ind. Eng. Chem. Res. 2005; 44(20): 7868–75.
5. Neumann K, Hunold S, Beer M de et al. Mass Transfer Studies in a Pilot Scale RPB with Different Packing Diameters. Ind. Eng. Chem. Res. 2018; 57(6): 2258–66.
6. Shi X, Xiang Y, Wen L-X, Chen J-F. CFD analysis of liquid phase flow in a rotating packed bed reactor. Chemical Engineering Journal 2013; 228: 1040–9.
7. Wang GQ, Xu OG, Xu ZC, Ji JB. New HIGEE-Rotating Zigzag Bed and Its Mass Transfer Performance. Ind. Eng. Chem. Res. 2008; 47(22): 8840–6.
8. Luo Y, Chu G-W, Zou H-K et al. Characteristics of a two-stage counter-current rotating packed bed for continuous distillation. Chemical Engineering and Processing: Process Intensification 2012; 52: 55–62.
9. Neumann K, Hunold S, Groß K, Górak A. Experimental investigations on the upper operating limit in rotating packed beds. Chemical Engineering and Processing: Process Intensification 2017; 121: 240–7.
10. Mersmann A (Hrsg.). VDI-Wärmeatlas: L2.6 Druckverlust und Flutgrenze in berieselten Packungen. Springer-Verlag GmbH Deutschland; 2019.
11. Singh SP, Wilson JH, Counce RM et al. Removal of volatile organic compounds from groundwater using a rotary air stripper. Ind. Eng. Chem. Res. 1992(31): 574–80.
12. Groß K, Bieberle A, Gladyszewski K et al. Analysis of Flow Patterns in High-Gravity Equipment Using Gamma-Ray Computed Tomography. Chemie Ingenieur Technik 2019; 91(7): 1032–40.
13. Rajan S, Kumar M, Ansari MJ et al. Limiting Gas Liquid Flows and Mass Transfer in a Novel Rotating Packed Bed (HiGee). Ind. Eng. Chem. Res. 2011; 50(2): 986–97.
14. Lockett MJ. Flooding of Rotating Structured Packing and its Application to Conventional Packed Columns. Chem. Eng. Res. Des 1995(73).
15. Groß KM. Deaeration in Rotating Packed Beds. Dissertation. Dortmund: TU Dortmund; 2021.
16. Bornhütter K. Stoffaustausch von Füllkörperschüttungen unter Berücksichtigung der Flüssigkeitsströmungsform. Dissertation. München; 1991.