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Hydrodynamic behaviour and mass transfer performance of SiC foam

Julien L  v  que(1), David Rouzineau(1), Michel Prevost(1), Michel Meyer(1)

- ◆ Universit   de Toulouse ; INP ; ENSIACET ; Laboratoire de G  nie Chimique ; Toulouse FRANCE
e-mail : Michel. Meyer@ensiacet.fr
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Abstract.

This work presents an experimental study of hydrodynamic behaviour and mass transfer performance of ceramic foam (SiC) as column packing. Foam studied is open celled from Sicat Company, their manufacturing method, which is well controlled, allows modifying the characteristics of foam like voidage, specific area and PPI (Pore Per Inch) number. Voidage of the foam studied is of 91% with $640 \text{ m}^2/\text{m}^3$ specific area and 5 PPI. Hydrodynamics experiments are realised with air-water system in counter current in a 150 mm diameter column with a packing height of one meter. Parameters studied are pressure drop for dry and wet packing, flooding and liquid hold-up.

Total reflux experiments with n-heptane/cyclohexane mixture were carried out in a distillation column at atmospheric pressure to study mass transfer by determination of HETP (Height Equivalent to Theoretical Plate).

Performance in term of pressure drop per unit height and flooding are quite lower in comparison with classical packings of distillation. Pressure drop obtained is about few millibars per meter ($0\text{-}10 \text{ mbar}\cdot\text{m}^{-1}$) for F-Factor from the range of 0 to 1 and liquid superficial velocities from 1 to $10 \text{ m}^3\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Liquid hold-up values, measured in the same range of flow, are in a range of 5 to 10%.

Key-words. Ceramic foam, Distillation, Packed bed, Structured packing, Pressure drop, Mass transfer efficiency

INTRODUCTION

Solid foam in general is a very attractive material due to their properties (low density, high porosity, high specific area, good thermal, mechanical, electrical and acoustics properties) and have a various range of applications. Interests on foam are lately growing for applications such as heat exchangers, reformers, mixing improvement and mainly as catalyst or structured catalyst supports.

Several hydrodynamics studies of foam have been made but generally with monophasic system. The works of Stemmet et al. [1, 2], hydrodynamic study of foam with biphasic system in counter current and study of gas-liquid mass transfer in co-current show that foam presents low pressure drop and good gas-liquid mass transfer. These promising results show that application of foam as packing for distillation is possible and could be interesting. Moreover, the foam material studied, β -SiC, is well adapted to catalyst coating; this foam was thus selected while thinking of a future application in reactive distillation. Before experiments in reactive distillation, a preliminary study of foam application in distillation must be realised.

The interest of foam as catalytic packing is to propose an alternative to classical catalytic packing. In fact, few catalytic packings have been developed and the most commonly packing used consists in catalyst particles sandwiched between corrugated sheets of wire gauze. The objective of foam catalytic packing is to reduce the amount of catalyst inside the column while keeping same efficiency in term of conversion and selectivity.

FOAM STRUCTURE

The foam preparation method developed by the Sicat company is based on the impregnation of a polyurethane foam with a resin. The final product exhibit similar morphology with the polyurethane foam and it permits the synthesis of foams with controlled cell sizes. Pore size (characterized by PPI number), void volume, and the apparent density are the parameters which may be modified. This allows the manufacture of materials with a wide variety of hydrodynamic properties. For this type of foam, the open void fraction is not dependent on the PPI number; in fact it is possible to maintain a constant open void fraction over the entire range of PPI numbers.

Our study is focused on open celled SiC foam with a single PPI number (5 PPI) and porosity (91%) corresponding to a specific area of $640 \text{ m}^2/\text{m}^3$.

EXPERIMENTAL SETUP AND METHOD

Hydrodynamics pilot plant

The experimental setup for hydraulic studies is illustrated in Figure 1. The hydrodynamic studies were performed in a 150 mm column for a packing height up to 90 cm at room temperature under atmospheric pressure. The column was operated with an air-water system in countercurrent.

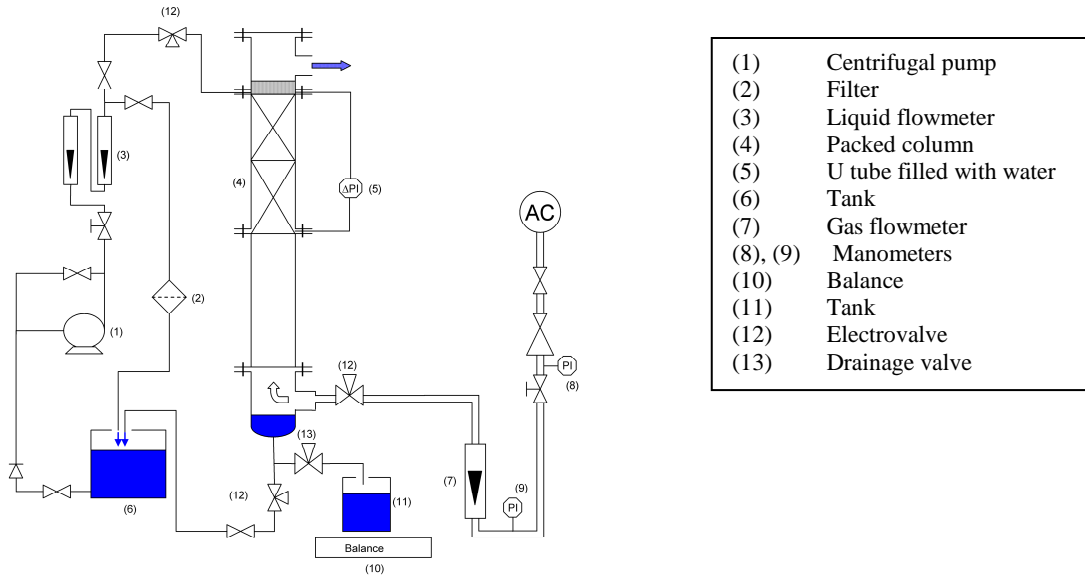


Figure 1. Experimental setup for hydraulic experiments

Method for hydrodynamics study

Liquid was supplied to the top of the column via a plate distributor for superficial velocities ranging from 1 to 10 $\text{m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. The gas flow was supplied at the bottom of the column for a range of F-Factor from 0 to 2.25 in the empty column. The pressure drop was measured using a U-tube manometer filled with water.

Measurements of liquid hold-up were also carried out using the same apparatus. Liquid hold-up, which represents the amount of liquid retained in the packing, is the sum of two components, the static liquid hold-up ($h_{L,s}$) and the dynamic liquid hold-up ($h_{L,d}$):

$$h_{L,t} = h_{L,s} + h_{L,d} \quad (1)$$

Dynamic liquid hold-up was measured using the drainage method. After reaching the steady-state conditions, the supply of liquid and gas was stopped. The draining liquid was collected for 30 min and measured using a balance. Static liquid hold-up may be determined from dynamic liquid hold-up results.

Distillation pilot plant

The mass transfer efficiency is characterized by the measure of HETP (Height Equivalent of Theoretical Plate) defined as the ratio of height of the packing by the number of equilibrium stages. The HETP experiments were performed using the distillation pilot plant described in Figure 2.

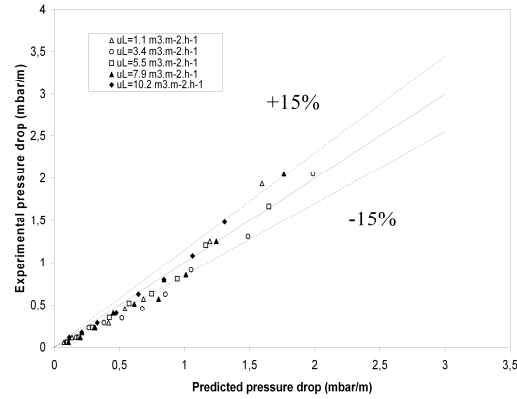


Figure 3. Parity plot between experimental wet pressure drop and predicted wet pressure drop

The pressure drop was also compared with three classical packing materials used for distillation, two structured and one random. These were Sulzer M250Y, widely used in industry, with a specific area of $250 \text{ m}^2/\text{m}^3$; Sulzer CY with a specific area of $700 \text{ m}^2/\text{m}^3$; and 5/8" Pall rings (denoted as PR 5/8) with a specific area of $360 \text{ m}^2/\text{m}^3$.

As an example, the pressure drop for one liquid loading is depicted in Figure 4 for $u_L = 7.9 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. The pressure drop of the foam is somewhat higher than the three other packing materials but in the same order of magnitude (several $\text{mbar} \cdot \text{m}^{-1}$).

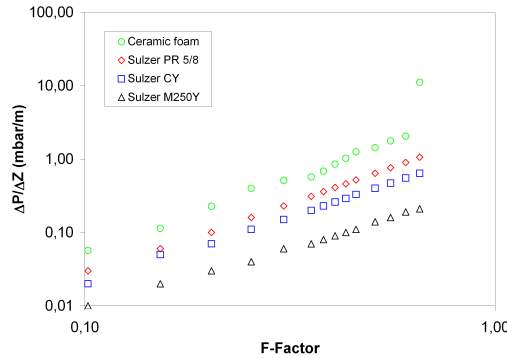


Figure 4. Pressure drop of ceramic foam, M250Y, CY and PR 5/8 for $u_L = 7.9 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$

In Figure 5, the dynamic liquid hold-up experimental results and predicted liquid hold-up are plotted for four liquid superficial velocities from 3.4 to $9.1 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. Predicted liquid hold-up is obtained by expressing liquid hold up as a power function of the liquid-phase Reynolds number:

$$h_L d = 0.0115 \text{Re}_L^{0.6} \quad (5)$$

Dynamic liquid hold-up is shown to be independent of the gas superficial velocity in the first part of the curve, while in the second part of the curve (the loading zone) the liquid hold-up increases with gas superficial velocity. Liquid hold-up is also influenced by the liquid superficial velocity, increasing as the velocity increases.

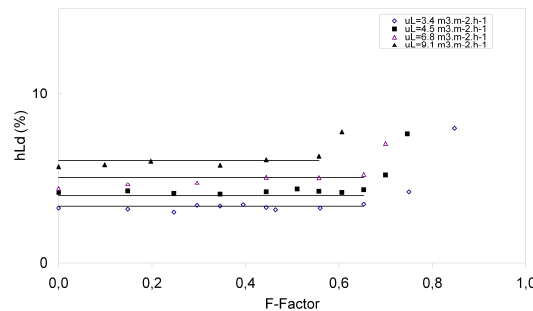


Figure 5. Dynamic liquid hold-up of ceramic foam as a function of gas velocity: Experimental (Marks) and predicted values (Straight line)

The comparison with other packing material is presented in Figure 6; the liquid hold-up of the foam is higher than the hold-up of M250Y and the Pall rings in the region before the loading zone but lower than the hold-up of CY. The increase in liquid hold-up occurs at lower liquid and gas velocities. Increased liquid hold-up at low F-Factors will result in high residence times.

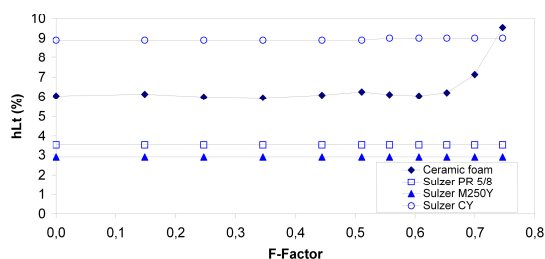


Figure 6. Liquid hold-up of ceramic foam, M250Y, CY and PR 5/8 for $UL = 4.5 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$

Mass transfer results

The results of HETP experiments performed under total reflux with an initial composition of 30% molar cyclohexane/70% molar n-heptane are presented in Figure 7 but also a comparison with the following systems:

- Sulzer M250Y with cyclohexane/n-heptane mixture at 1.65 bar ($250 \text{ m}^2/\text{m}^3$ specific area)[5]
- Sulzer CY with chlorobenzene/ethylbenzene mixture at 0.4 bar ($700 \text{ m}^2/\text{m}^3$ specific area)[6]
- Pall rings (5/8") with methanol/2-propanol mixture at atmospheric pressure ($360 \text{ m}^2/\text{m}^3$ specific area)[7]

The experimental HETP values of ceramic foam fell between 0.2 and 0.3m with increasing mass transfer with increasing gas and liquid superficial velocities inside the packing. In fact, operating HETP will be 0.2 m because 0.3 m corresponds to low F Factor involving a bad wetting. This corresponding to approximately 4-5 theoretical stages per meter. The mass transfer efficiency of the foam packing is higher than M250Y and P/R 5/8 but lower than CY. Therefore, the foam packing can be considered to have very good mass transfer performance.

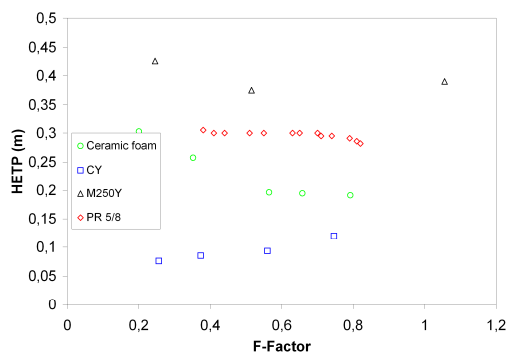


Figure 7. Comparison of HETP for ceramic foam, M250Y, CY and PR 5/8

CONCLUSION

This work presents a detailed investigation of the use of SiC ceramic foam as a distillation packing material. The principal hydraulic characteristics of the foam determined for air/water system in countercurrent were quite low compared with classical distillation packing materials (M250Y, CY, and Pall rings).

Pressure drop were predicted by using the approach of Lacroix et al. [4] while dynamic liquid hold-up was modelled as a function of the liquid phase Reynolds number.

The mass transfer efficiency is very good with a HETP of 0.2 m and increasing mass transfer with increasing gas and liquid superficial velocities inside the packing.

Based on these results, ceramic foams could be considered as a good potential packing for distillation, however the applications would be limited by the low capacity.

In the target application of reactive distillation, the low capacity does not represent a real disadvantage because the flow rates are lower. Moreover, increased liquid hold-up at low F-factors implies a high residence time, which would be favourable to the reaction. The next step of the study consists in tests of catalyst coatings on the foam and reaction kinetics measurements.

C _g :	Loading factor at flooding (m.s ⁻¹)
dp:	Mean particle diameter (m)
E ₁ , E ₂ :	Constants in Ergun's equation
F:	Gas load (Pa ^{0.5})
HETP:	Height Equivalent to a Theoretical Plate (m)
h _{Ld} :	Dynamic liquid hold-up
h _{LS} :	Static liquid hold-up
h _{Lt} :	Total liquid hold-up
Re _L :	Liquid phase Reynolds number
u _G :	Superficial gas velocity (m.s ⁻¹)
X:	Sherwood abscissa
Z:	Height (m)
ε:	Open void fraction (%)
ΔP/ΔZ:	Pressure drop per unit packed height (mbar.m ⁻¹)
ρ _G , ρ _L :	Density of gas and liquid (kg.m ⁻³)
μ _G , μ _L :	Dynamic viscosity of gas and liquid (Pa.s ⁻¹)

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