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A Novel Potential Application of SiC Ceramic Foam Material to Distillation: Structured Corrugation Foam Packing

Hong Li, Ying Meng, Jing Zeng, Xingang Li, Xin Gao*

School of Chemical Engineering and Technology, National Engineering Research Center of Distillation Technology,
Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin University, Tianjin 300072, China
gaoxin@tju.edu.cn

Applications using polymer-derived ceramic foam material as distillation packing or trays have demonstrated higher performance than classical mass transfer units, except for the operation range [Leveque et al., 2009; Gao et al., 2015]. To overcome this disadvantage, a series of novel mass transfer units based on the polymer-derived ceramic foam material have been developed, such as Foam Monolithic Tray, Structured Corrugation Foam Packing (SCFP) and so on. In this paper, the hydrodynamic performances and mass transfer efficiency of a SCFP-SiC is examined, with special emphasis on the effect of the foam cell size and sheet thickness. The hydraulic performance parameters and the mass transfer efficiency of SCFP are measured as 100 mm i.d. diameter. The experimental values are compared with the traditional column packings. In general, the comparison results indicate that the hydrodynamics and mass transfer performances of SCFP meet the requirements for the mass transfer elements in the distillation column. Besides, this paper also made the measurement of the SCFP-SiC in the air separation systems. The experiments indicated that SCFP has the high theoretical stages and the low pressure drop for the air separation system. The results also indicate that the SCFP has higher operation flexibility and significantly enhance the efficiency of vapor-liquid mass transfer at the industrial scale for clean system.

Key words：Ceramic foam; Distillation; Structured packing; Mass transfer efficiency; Air separation

1. Introduction

Foams (ceramic, metal, carbon, SiC, polymers, etc.), new materials, have developed in recent years because of their advantages such as good abrasion and corrosion resistance, high porosity and surface area, attractive thermal, mechanical, electrical, and acoustical properties [Li et al., 2015a, Li et al., 2016; Yan et al., 2018]. As a result, these foams have been widely used in chemical industry, especially in the field of distillation [Fan et al., 2016; Ou et al., 2017]. High specific surface area and high porosity characteristics make them have low pressure drop and high mass transfer coefficient [Li et al., 2015b, 2018; Stemmet et al., 2005, 2007]. Lévêque et al [2009] designed monolithic foam packing (MFP) with a diameter of 150 mm and a height of 100 mm. Research results indicated that this packing had high wet pressure drop, small operating range, high liquid hold-up and high mass transfer efficiency. But its monolithic structure causes a poor gas-liquid distribution. Therefore, the applications of foam materials in vapor-liquid mass transfer process would be limited by the low capacity.

In order to solve the problems mentioned above and apply the foam silicon carbide materials to the distillation, this article develops a new type of SiC structured corrugation foam packing (SCFP-SiC, Chinese Patent CN102218293A) which combines the advantage of ceramic foam and corrugated structure packing. The hydrodynamic characteristics including wet pressure drop, flooding line and liquid holdup and mass transfer efficiency (HETP) of SCFP-SiC were tested and compared with the classical packings, monolithic foam packing and BX gauze packing. Besides, the influence of the main structure parameters on the performances of SCFP-SiC is also investigated to guide the design of industrial application. The air is a clean, no-scale and unchokeable separation system. Considering these features of air separation system, the optimization structure of SCFP-SiC was used in the air separation systems for the sake of the application performance of SCFP-SiC at last.

2. Experiment

2.1 Structure parameters of SCFP-SiC

The photograph of SCFP-SiC that was formed as a whole is shown in Figure 1. Then they were cut into cylindrical shape with a diameter of 100 mm and a height of 100 mm by arc surface cutting. Moreover, polytetrafluoroethylene was used to closely wind these packings before they were filled into the tower. These steps could reduce the side effects and wall flow by a large margin. The characteristic parameters of SCFP-SiC and BX were shown in Table 1 that indicates that SCFP-SiC and BX have the same structure as 500X.

Table 1 Characteristic parameters of packing

Type	Wave height /mm	Wave distance/mm	Corrugation angle/°	Sheet thickness/mm	Void volume /%	Pore size of foam martials /mm
SCFP-SiC	6.3	10.2	30	1	92.5	3
BX	6.3	10.2	30	0.15	90	none

Figure 1: SiC Structured Corrugation Foam Packing (SCFP-SiC)

2.2 Experimental set up and methods

Hydrodynamics experiment: The hydrodynamic experiment was carried out in a Plexiglas tower of 100 mm internal diameter, which has 800mm height packing. These tests were implemented at room temperature and atmospheric pressure, with air-water countercurrent biphasic system. Liquid was circulated from a tank and distributed on the top of the column by a plate distributor with approximately 1000 holes per square meter. It flowed from the top of packing to the bottom and was finally collected in the tank. Gas was taken from draught fan and flowed upward from bottom to top. The liquid superficial velocities were changed from 0 to 60 m^3/m^2h and the gas superficial velocities were changed from 0 to 3.6 m/s. The pressure drop over the packing was measured with a U-tube manometer filled with water with an accuracy of 5 Pa.

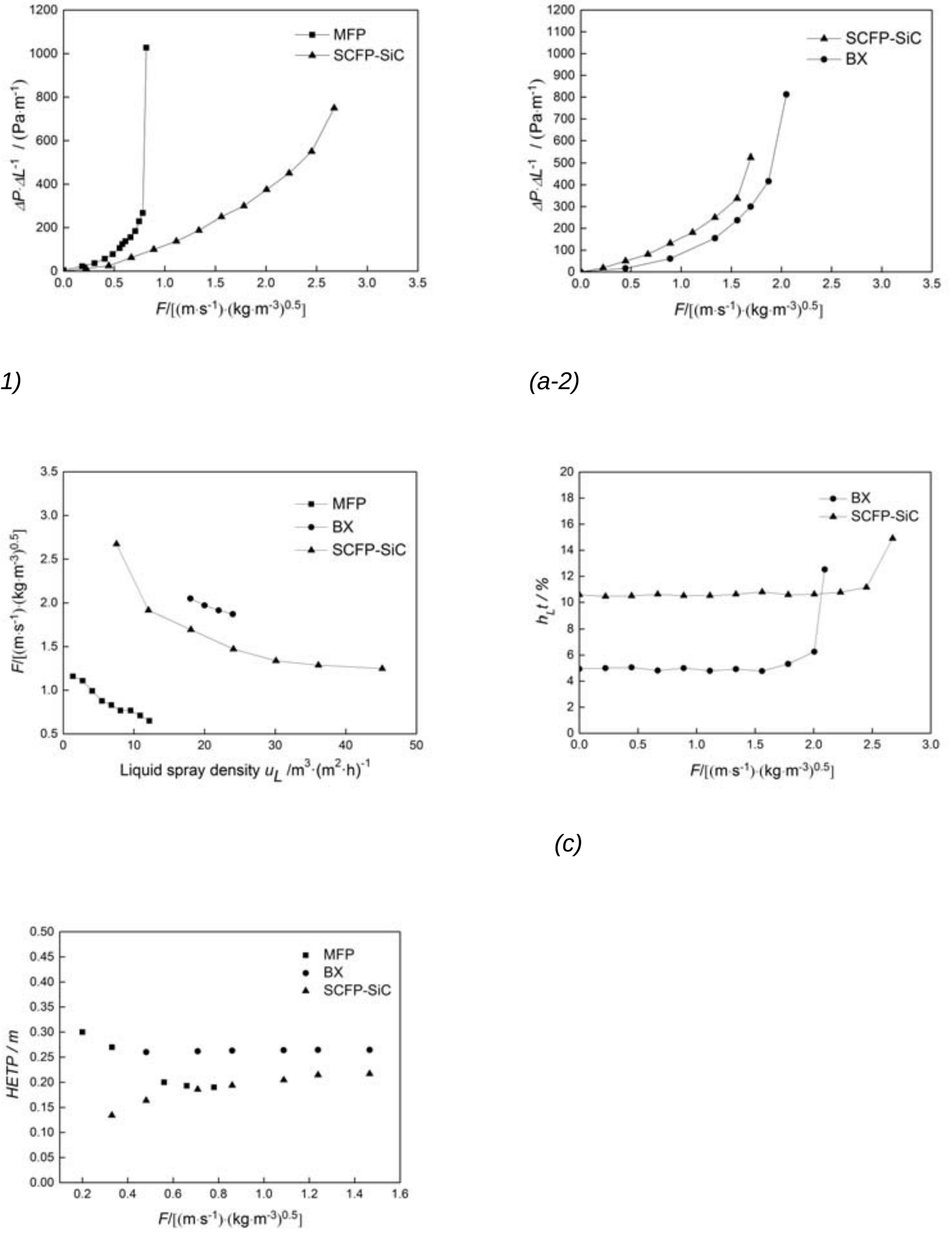
Mass transfer experiment: The glass tower had the same internal diameter and packing height as the hydrodynamic experiment set up. Experiments were carried out by total reflux experiments, using a standard cyclohexane /n-heptane mixture [Lévêque et al., 2009] at atmospheric pressure. This mixture was heated by the heat conducting oil in the reboiler and cooled on the top of tower by the water. The duties of reboiler ranged from 2 to 12KW. The reboiler and column were wrapped with insulation material to avoid the heat loss.

Air separation experiment: The air separation experiment was carried out in a stainless-steel column of 343 mm internal diameter and a packing height of 2000mm. This column was equipped with a condenser and a reboiler. The feed stream was the mixture of O_2 and N_2 or the mixture of O_2 and Ar that was compressed and cooled to approach to the dew point temperature under the low pressure. This feed stream, entering at the bottom of the column, was distilled into a high purity gaseous stream and a high purity liquid stream. The gaseous stream was condensed by the condenser to produce the liquid reflux stream at the top and the liquid stream was gasified by reboiler to produce the gaseous reflux stream at the bottom. Whereafter, theses reflux streams were introduced to the top of the column or the bottom of the column, respectively. Meanwhile, the top reflux stream and the bottom liquid stream both installed the timing sampling device. The samples were measured by oxygen meter.

3.Results and Discussion

3.1 Performance comparison

Figure 2 (a-1) shows the wet pressure drop of SCFP-SiC and MFP in the liquid spray density of 7.5 m^3/m^2h. MFP has higher wet pressure drop and it firstly comes to the flooding point. The recurring reason of this phenomenon is that the gas and liquid twisted and turned inside the MFP rather than distributed homogeneous. The wet pressure drop of SCFP-SiC is higher than BX in the liquid spray density of 18 m^3/m^2h as shown in the Figure 2 (a-2). This is probably due to SCFP-SiC has the thicker sheet thickness than BX. The sheet thickness of SCFP-SiC is 1mm. However, the sheet thickness of BX is only 0.15 mm. So, SCFP-SiC has the less area of gas passageway compared with BX. Not only that, the coarser surface of SCFP-SiC than BX, although they have the same structure. Therefore, compared with MFP and BX, SCFP-SiC still has a relatively acceptable wet pressure drop.



(a-1) *(a-2)*

(b) *(c)*

(d)

Figure 2: Performance comparison of SCFP-SiC, MFP and BX (a)-1 wet pressure drop of SCFP-SiC and MFP in the liquid spray density of 7.5 m^3/m^2h (a-2) wet pressure drop of SCFP-SiC and BX in the liquid spray density of 18 m^3/m^2h (b) flooding curves (c) dynamic liquid holdup (d) HETP

The flooding curves of SCFP-SiC, MFP and BX are shown in the Fig.2 (b). The flooding F-factors (Y axis) of three these packings are gradually reducing with the increasing of liquid spray density (X axis), which means the higher of the liquid spray density has, the easier the packing begins to flood. Compared with other common packings under the same liquid spray density, MFP has the lowest flooding F-factor which means MFP is the easiest one to flood. Therefore, the distillation operating range of MFP will be largely restricted because of its poor distribution of gas and liquid. Meanwhile, the flooding curve of SCFP-SiC is slightly lower than that of BX on account of a thicker sheet thickness of SCFP-SiC. Therefore, compared with BX, SCFP-SiC has the less gas passageway, which will be easier to cause flooding.

Figure 2 (c) depicted the comparison with the dynamic liquid holdup of BX. The total liquid holdup values in the first part curve for SCFP-SiC and BX are 10.5% and 5% respectively at the liquid spray density of 7.5 m^3/m^2h. The liquid hold-up of SCFP-SiC is higher than the hold-up of BX before the loading zone. Experiments show that the contact angle of SiC ceramic foam material and water is 44°, while the contact angle of wire netting and water is 70°. The SiC ceramic foam material has a smaller contact angle and a strong adsorption of water. Therefore, the wettability of SCFP-SiC is better than BX. Besides, the special three-dimension network structure of foam material increases the effective channel for the flow of liquids. All of these characteristics can give rise to high hold-up. Meanwhile, the rapid increase of dynamic liquid holdup for BX occurs at lower gas and liquid velocities.

The results of HETP experiments for SCFP-SiC, MFP and BX are shown in Figure 2 (d). The HETP of SCFP-SiC rises from 0.1m to 0.2m (without the loading zone) with the increasing of F-factor, corresponding to approximately 5-6 theoretical stages per meter. SCFP-SiC has a higher liquid holdup than BX as previously mentioned. The three-dimensional connected skeleton network of foam material provides a larger contact area for gas and liquid. Moreover, the liquid can flow inside the foam pore, and mass transfer with vapour at the edge of foam materials [Li, et al., 2012]. Therefore, the HETP of SCFP-SiC is much lower than HETP of BX. The HETP of MFP is between the SCFP-SiC and BX. Furthermore, its variation tendency is different from SCFP-SiC and BX on account of its different structure. This monolithic structure also leads to its poor operating range. Therefore, foam material and structured corrugation structure give SCFP-SiC an extraordinarily significant mass transfer performance.

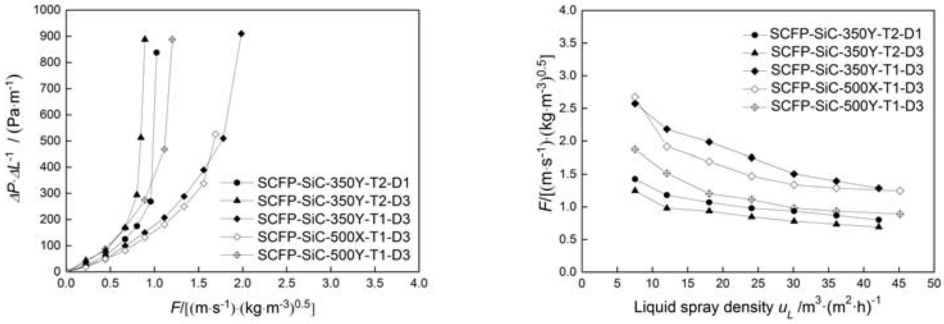
3.2 Structure optimization of SCFP-SIC

A series of SiC ceramic foam structured packings were tested. Their characteristic parameters, specific area, corrugation angle, foam diameter, sheet thickness, are shown in Table 2. Through comparing the hydrodynamic and mass transfer efficiency of these SiC ceramic foam structured packings, the influence of these characteristic parameters on SCFP-SiC will be achieved.

Table 2 Characteristic parameters of SiC ceramic foam structured packings

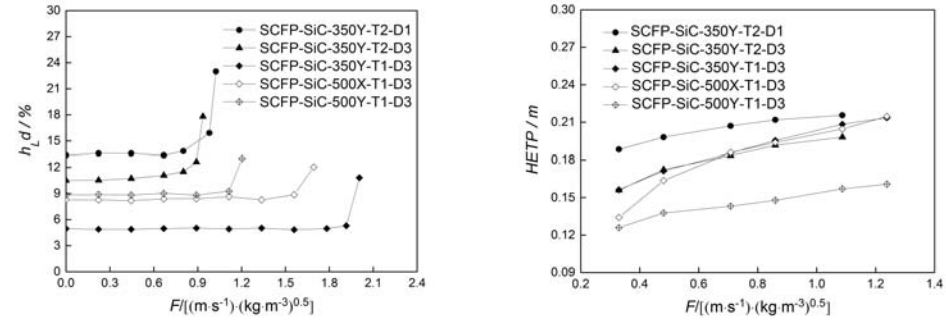
Type	Wave height /mm	Wave distance/mm	Corrugation angle/°	Sheet thickness/mm	Foam diameter /mm
SCFP-SiC-350Y-T2-D1	9	15	45	2	1
SCFP-SiC-350Y-T2-D3	9	15	45	2	3
SCFP-SiC-350Y-T1-D3	9	15	45	1	3
SCFP-SiC-500X-T1-D3	6.3	10.2	30	1	3
SCFP-SiC-500Y-T1-D3	6.3	10.2	45	1	3

Figure 3 show the main performance parameters (wet pressure drop (a), wet flooding curves (b), dynamic liquid hold up (c) and mass transfer (d)) of five types of SiC ceramic foam structured packings for liquid spray density 18 m^3/m^2h. The wet pressure drop and the dynamic liquid holdup are increase following the adding of specific area and corrugation angle. However, the flooding curves and the HETP have the opposite results. These variation tendencies are the same as common plate corrugated packing. As shown in Figure 3 (a), the pressure drops also add with the increasing of sheet thickness on account of the reducing the space between adjacent corrugated sheets. The raising of the foam diameter will cause the increasing of the wet pressure drop. Because the surface of SCFP-SiC is coarser with the increase of the foam diameter. Due to the same reason as the wet pressure drop, the flooding F-factors decrease with the adding of foam diameter and sheet thickness in Figure 3 (b). As shown in Figure 3 (c), the liquid holdup reduces with the increasing of foam diameter because of stronger adsorption of water and better wettability in the case of smaller foam diameter. Nevertheless, by reason of larger liquid storage space, the thicker sheet thickness will result in the increscent liquid holdup. Moreover, the HETP decrease with the increasing of foam diameter and sheet thickness in Figure 3 (d). Because bigger foam diameter and thicker sheet thickness of SCFP-SiC provide more contact surface for gas and liquid. Compared with BX, all these SCFP-SiC have a higher mass transfer performance. The theoretical stages per metre of SCFP-SiC-500Y-T1-D3 can reach to approximately 7.



(a) wet pressure drop

(b) flooding curves



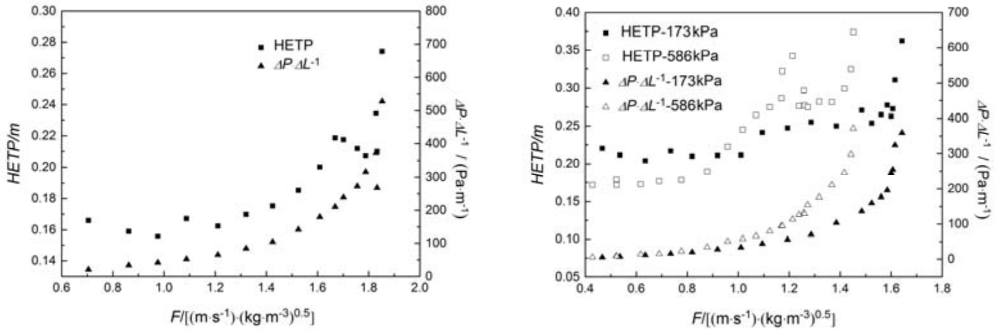
(c) dynamic liquid holdup

(d) HETP

Figure 3: main performance parameters for SCFP-SiC with different specific area, corrugation angle, foam diameter and corrugated thicknesssheet thickness

3.3 Air Separation

In order to examine the performance of SiC ceramic foam structured packings for air separation system, the mixture of O_2 and Ar or the mixture of O_2 and N_2 are chosen to experiment. At the same time, 173 and 586 kPa were selected for the O_2 and N_2 separation system to test the influence of column pressure. The HETP and pressure drop results of SCFP-SiC for the O_2 and Ar separation system are shown in Figure 4 (a). It is indicated that the HETP of SCFP-SiC rises from 0.15m to 0.27m with the increasing of F-factor. Furthermore, the pressure drop of SCFP-SiC also increases along with the increasing of F-factor. The pressure drop is only around 200 Pa, when the F factor is 0.7.



(a) O_2 and Ar

(b) O_2 and N_2

Figure 4: HETP and pressure drop for SCFP-SiC in air separation system

Figure 4 (b) are shown to present the HETP and pressure drop results for the O_2 and N_2 separation system under 173 kPa and 586 kPa respectively. Same as the Figure 4 (a), the HETP and the pressure drop both are rises with the F-factor increasing in the O_2 and N_2 separation system. For this separation system, SCFP-SiC also has the excellent performance. So, the SiC ceramic foam structured packings can be applied in the air separation systems. The comparison with the experiment results under 173 kPa and 586 kPa shows that the higher pressure of the column can bring about higher theoretical stages per meter. However, the higher pressure also can lead to the higher pressure drop, which is adverse to the operation for the distillation.

4. Conclusion

This paper tested the hydrodynamics and mass transfer performance of SCFP-SiC. These performance results were compared with MFP and BX gauze packing. The hydrodynamic experiment showed the SCFP-SiC had the similar hydraulic characteristics as BX gauze packing because of their same packing type. Compared with the MFP, the corrugated structure could largely reduce the wet pressure drop and extend the flooding F-factor. Meanwhile, the SiC ceramic foam structured packing had foam structure and higher wettability which lead to the higher liquid holdup than BX packing.

Besides, SCFP-SiC also had higher mass transfer efficiency with approximately 5-7 theoretical stages per meter. In a word, SiC ceramic foam structured packing has a better hydrodynamics and mass transfer performance than MFP and BX gauze packing. Moreover, foam diameter has a slighter effect on the hydrodynamics performance of SCFP-SiC and a relatively larger effect on the mass transfer performance. However, the sheet thickness has the opposite effect degree. These influencing factors can guide the design of an exactly type of SCFP-SiC according to the demand.

At last, the paper presented a detailed investigation of the SiC ceramic foam structured packing for air separation systems. The experiment results show that SCFP-SiC has the high theoretical stages and the low pressure drop for the O_2 and Ar separation system or the O_2 and N_2 separation system. Therefore, the SiC ceramic foam structured packing can be suggested to apply in the air separation systems.

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