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Combination of spiral nozzle and column tray leading to a new direction on the distillation equipment innovation

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ABSTRACT

The hydrodynamics and mass transfer performance of a novel spiral nozzle tray (SNT), using the commercial spiral nozzle as the mass transfer element, was investigated in this research. The hydrodynamic performance parameters include pressure drop, weeping, clear liquid height and entrainment. All the experiments were conducted in an air–water system under atmospheric pressure. The mass transfer efficiency of the SNT was studied in a stainless steel column for separating the mixture of cyclohexane and *n*-heptane. The bubble visualization experiment was set up to determine the cause why the SNT had such particular mass transfer efficiency. The results indicate that the SNT can be considered as a promising tray for distillation. Combining the spiral nozzle with the column tray will be a new direction for the development of the column internals.

1. Introduction

The plate distillation column is a typical type of separating equipment, has been widely used in the oil refining and chemical industries. Column trays, where gas and liquid contact on, play a critical role in the performance of distillation column [1]. Mature in their development, sieve trays and float valve trays have been reported as the two most common plates in chemical industries [2–5]. In spite of all of the pristine methods and research attention, sieve trays and floating valve trays are still not completely quantified and fully satisfied for industrial requirements. The limitations of sieve trays include weeping and limited operating flexibility, while excessive manufacturing cost, high pressure drop and bad anti-choking are the main drawbacks of float valve trays. Also, the float valves can easily break off from the tray [6–10]. As a hybrid of the sieve tray and the floating valve tray, the fixed valve tray has been developed to adopt the advantages and avoid the disadvantages of both above mentioned trays. The manufacturing cost of the fixed valve tray is closed to that of the sieve tray, and the flexibility is similar to that of the floating valve tray. Due to the existing superiority and unknown potential, the fixed valve tray has been drawing more attention and is recently becoming a major research and industrial interest in the field of column tray [11,12]. As such, designing a column tray with higher mass transfer efficiency, larger capacity and operating flexibility, as well as lower pressure drop has great potential.

With a peculiar structure like aiguille, spiral nozzles (Fig. 1a) are mainly designed for atomizing liquids. Unlike common spray nozzles completing liquid atomization via vary high hydraumatics, when they pass through the cavity of spiral nozzles, liquids hit the spiral atomizing surface and become micro droplets, which squirt out in the tangential direction of the atomizing surface (Fig. 1b). In comparison to common spray nozzles, spiral nozzles need a lower hydraumatic and have a better anti-choking performance and simpler structure which decreases the manufacturing cost [13]. Recently, a variety of spiral nozzles have been applied in the industrial processes of chemical engineering, environmental protection, electricity, and cottonocracy etc. [14,15]. Because of the particular hydraulics characteristic of the spiral nozzle, the authors reckon that it has the potential to be an outstanding mass transfer element when applied to column trays for distillation process. Therefore, a novel column tray with the spiral nozzle fixed valve was designed.

In this research, hydrodynamics and mass transfer experiments were set up to evaluate the performance of this novel fixed valve tray. The experimental setups and methods were described in the next section. In hydrodynamics experiments, pressure drop, clear liquid height, weeping, and entrainment of the spiral nozzle

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Nomenclature

A	tray area ($\mathrm{m^2}$)
A_P	hole area ($\mathrm{m^2}$)
C	constant
E_T	mass transfer efficiency
e_V	entrainment (%)
F_0	gas F-factor through holes $(\mathrm{m/s})(\mathrm{kg/m^3})^{0.5}$
F_T	gas F-factor through empty column, $(\mathrm{m/s})(\mathrm{kg/m^3})^{0.5}$
h_L	clear liquid height (mm)
h_W	overflow weir height (mm)
L_W	liquid weir loading ($\mathrm{m^3\ m^{-1}\ h^{-1}}$)
m	constant
n	number of holes
N	theoretical plate number
N_P	actual plate number
ΔP_d	dry plate pressure drop (Pa)
ΔP_w	wet plate pressure drop (Pa)
t	hole pitch (mm)

Greek letters

$\alpha, \beta, \gamma, \eta$	constant
φ	opening ratio (%)

Subscripts

d	dry
L	liquid
T	total
V	gas
w	wet
W	weir

tray (SNT) were measured under different operating conditions, while overall column efficiencies of the SNT were obtained from the mass transfer experiments. Also, hydrodynamics and mass transfer properties of the SNT were estimated and discussed with comparison to traditional column trays. Corresponding mathematical relationships for hydrodynamics characteristics were constructed for the understanding and design of this novel column tray. Moreover, the bubble visualization experiment was set up to observe the bubbles from single spiral nozzle at different conditions, which contributes to the better understanding of mass transfer efficiencies.

2. Experimental setups and methods

2.1. Structure of the SNT

Through a long period of development, spiral nozzles have already for the most part been standardized. The spiral nozzle applied in our experiments was also selected from the standard ones. According to the design experiences of column trays, we found that the spiral nozzle (Fig. 2a) with 3/8 inch external diameter is the most appropriate type to be the mass transfer element. Manufactured in plastic, the selected spiral nozzle has a 16.8 mm external thread in diameter. Also, the corresponding nuts were used for fixing the spiral nozzles on the tray. The internal cavity of the spiral nozzle has an 11 mm diameter at the inlet. After being combined with the column tray, the top of the spiral nozzle is 34 mm height from the tray floor.

In Fig. 2, it also exhibits the structure of SNTs for hydrodynamics and mass transfer experiments. The frame of trays was made of stainless steel to guarantee mechanical strength. Considering the inlet diameter of each spiral nozzle, the spiral nozzles were arranged in proper quantity on the tray following the design principle of sieve tray. As a result, the SNT with 5.71% opening ratio (based on the whole tray area, hole pitch $t = 26$ mm) was designed for hydrodynamics experiments, while those with 2.82%, 4.17% and 6.05% opening ratio (based on whole tray area, hole pitch $t = 30$ mm, 26 mm, 22 mm respectively) were designed for the mass transfer experiments. In Table 1, details of the geometric information of SNTs have been presented.

The commercial sieve tray (7.50% opening ratio) and the new type of fixed valve tray (9.57% opening ratio) that have been co-developed by Tianjin University and Sinopec Engineering Inc. (SEI) are adopted as the comparisons [12]. Considering the hydrodynamics and mass transfer characteristics of these two kinds of trays have already been tested by our research group, the contrast tests were not arranged [12,16].

2.2. Hydrodynamics pilot plant

The hydrodynamic experiment setup is presented in Fig. 3. It is an organic glass column with 600 mm inner diameter and 2500 mm height. When testing, two SNTs were placed in the setup with 400 mm tray spacing. The upper tray was for testing, while the lower one was for the feed gas distribution. The inclined drip catcher and the screen packing above the test tray were used to

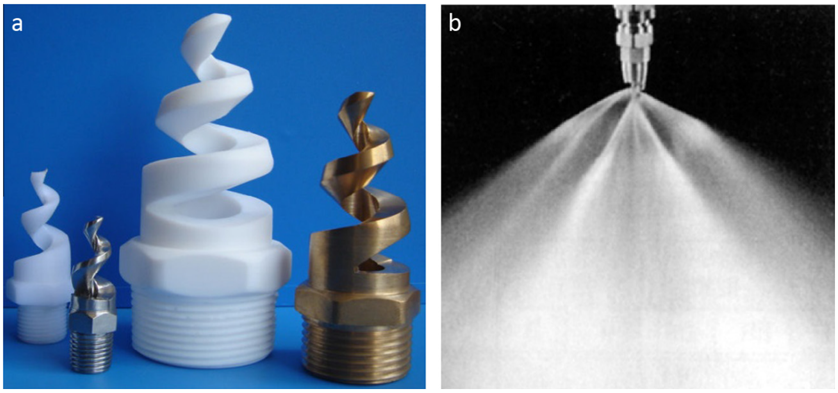

Fig. 1. Illustrations of spiral nozzle: (a) spiral nozzles made by different materials; (b) snapshot of the spray through a spiral nozzle.