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# Droplet Size Distribution on the Large-holed Compound Sieve Tray in the Spray Regime*

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**Abstract** The droplet size distribution with large-holed compound sieve tray operating in the spray regime is measured by using a double electrical probes technique in a cold model column of 400 mm diameter. The results indicate that the hole $F$-factor $F_0$ and surface tension are the main factors which influence the liquid dispersion expressed by the Sauter mean diameter $D_{32}$. A correlation of $D_{32}$ on surface tension, viscosity, $F$-factor, weir height and liquid flow rate is proposed.

**Keywords** double electrical probe, droplet size distribution, large-holed compound sieve tray, spray regime

## 1 INTRODUCTION

Multiphase flow is a common phenomenon in chemical processes. Liquid is used as dispersion phase in many cases. In the spray (gas continuous) regime, the mass transfer area between vapor and liquid phases depends on the surface area of droplets. Thus it is important to measure the droplet size and size distribution accurately to study the hydrodynamics and mass transfer in the spray regime.

Hitherto, the measurement methods for droplets include photographic method, optical scattering[1] and electrical probe technique[2–4], *etc.* Due to the difficulty of direct photography in real time and that of optical scattering for dense droplets, the two methods are not used widely in practical measurement of droplets. The single electrical probe technique is generally adopted. The electrical probe technique proposed by Geist *et al.*[5] has been improved in many ways[2–4]. Lü *et al.*[6–8] have analyzed the principle of the electronic measurement and determined the distribution of droplet sizes in gas-liquid flow. Using single electrical probe, Ma[9] has measured the droplets size and size distribution in real time in a sieve tray column with hole diameter of 12.5 mm and hole free area of 10.2% operating in the spray regime. The droplet population above the trays is not dense. However, high drop density occurs on large-holed sieve trays, which have large hole diameter, large free area and operating in the spray regime. The droplet size and size distribution will not be easily measured accurately by using single electrical probe because of the collision interference *i.e.* hanging-drop. Double electrical probes may overcome the disadvantage. Wicks[10] primarily proposed a method of double electrical probes. However, the mathematical model and the calculating method given by Wicks are unsuitable for application. Zhang *et al.*[11] corrected Wicks' mistakes, and described a new calculating method. Chen *et al.*[12] have measured the droplet size and size distribution on rotating stream tray using the double probes sensor system. Chen and Pan[13] also investigated the initial rate of droplet flow on a rotating stream tray by using the double probes sensor system. Liu *et al.*[14] used it to measure the initial projection velocities on sieve trays in spray regime.

In this work, the droplet size distribution above the compound sieve tray composed of structured packing and large-holed sieve tray with large free area is measured by using a double electrical probes improved further by Zhang *et al.*[11] Factors effecting on the droplet size distribution are also discussed.

## 2 MEASURING METHOD

The measuring method of double electrical probes technique is given in Fig. 1[11]. Two closely spaced probes have a distance $S$ in a moving droplet field. When an electrical conducting drop touches these two probes simultaneously, a current pulse passes through a resistor and cause a voltage pulse, which can be counted by an electronic counter.

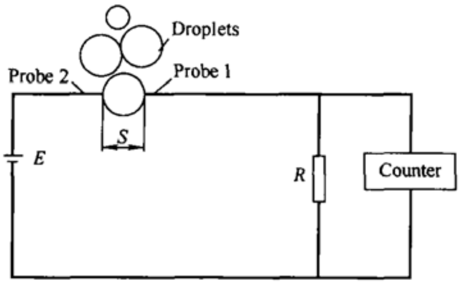

**Figure 1 Schematic diagram of measuring method**

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In a time interval $T$, $C$ ($S$, $T$) pulses are produced, indicating $C$ droplets with diameters equal or greater than $S$. By varying, $S$, it is possible to determine experimentally the dependence of $C$ on $S$.

The accuracy of double probes technique for measuring droplet sizes is determined by the precision of space $S$. Controlled by a stepping motor, space $S$ between the two probes can be adjusted from 0 mm to 7 mm automatically. The resolution ratio of $S$ can reach $8.34 \times 10^{-6}$ m[11]. The measuring deviation is not greater than 10% in the two phase flow of vapor and liquid[15].

Droplet size can be described by the Sauter mean diameter $D_{32}$. This diameter is defined as $D_{32} = \sum N_i D_i^3 / \sum N_i D_i^2$. From experimental data of $C$ ($S$, $T$), we can calculate the Sauter mean diameter of droplet and size distribution $f(D)$.

## 3 EXPERIMENTAL

A schematic diagram of the experimental apparatus used for measuring the drop size distribution is shown in Fig. 2.

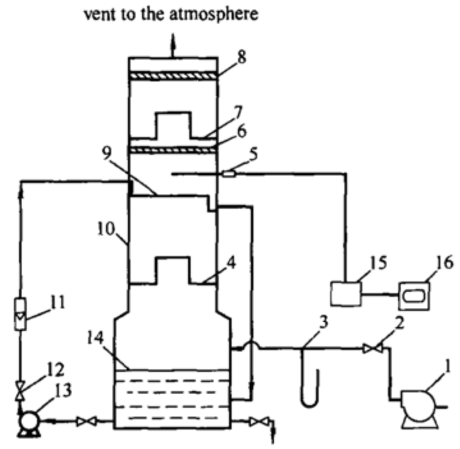

**Figure 2 Experimental apparatus**
1—air blower; 2—dish valve;
3—pitot tube and differential manometer;
4—gas distribution plate; 5—probe;
6—structured packing; 7—entrainment catch plate;
8—structured packing; 9—test plate; 10—tower;
11—flowrator; 12—valve; 13—pump; 14—cistern;
15—signal processor; 16—computer

The compound tray is composed of structured packing and large-holed sieve tray. The height of packing is 600 mm above the test plate. Details of the test large-holed sieve tray are 400 mm diameter, hole diameter 15 mm and free area 30%. In experiments, an inlet weir was used and the outlet weir was 20 mm.

The double electric probe was purchased from Beijing Institute of Chemical Technology. It was small enough, so that it would not disturb the dispersion in measurement. For all runs, the probe was positioned at the center of the tray for a height varied from 10 mm to 50 mm above the tray floor. In order to investigate the droplet size distribution on a plane, it was necessary to put the probe along the radial position from center to the wall of the column.

The air/water system was firstly used to measure the droplet size and size distribution. For investigating the effect of liquid properties on $D_{32}$, polyacrylamide and Tween were used. Addition some polyacrylamide into water changed the viscosity of liquid. As the amount of polyacrylamide is little, the change of liquid desity and surface tension is small. Tween is added into water to change the surface tension of liquid. Similarly, because of small amount of Tween, the change of liquid density and viscosity is negligible.

## 4 RESULTS AND DISCUSSION

Figure 3 shows typical data of $C$ ($S$, $T$). There are large number droplets when the distance $S$ between two probes is small. Number of droplets decreases rapidly when $S$ increases. till reaching zero. In all runs droplets ranging from $5.0 \times 10^{-5}$ to $7.0 \times 10^{-3}$ m could be detected. From experimental data of $C(S,T)$, the droplet size distribution was calculated. A typical curve of size distribution $f(D)$ is shown in Fig. 4.

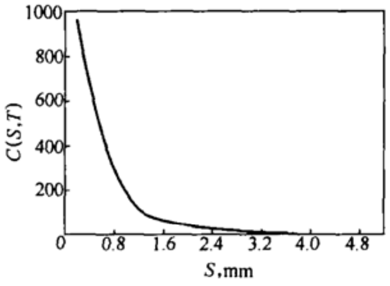

**Figure 3 $C(S,T)$ vs. $S$**

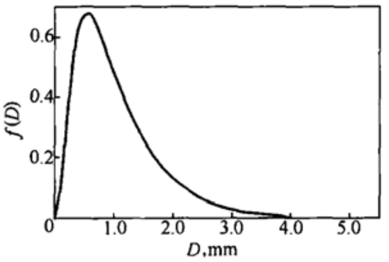

**Figure 4 A typical droplet size distribution $f(D)$**

### 4.1 Effect of gas velocity on $D_{32}$

Under the same liquid loading, Sauter mean diameters $D_{32}$ is plotted against column superficial $F$-factor $F_T$, as shown in Fig. 5. $F_T$ is defined as $u_T\sqrt{\rho_G}$, where $u_T$ is the column superficial velocity.

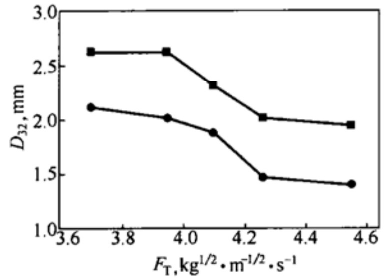

**Figure 5** Effect of superficial $F$-factor on $D_{32}$
($L_w = 3.1\,m^3{\cdot}h^{-1}{\cdot}m^{-1}$)
$H$, cm: ■ 10; ● 30

It can be seen from Fig. 5 that $D_{32}$ decreases when the superficial $F$-factor increases. As we know, the kinetic energy of gas increases with the superficial $F$-factor, which can break liquid into smaller drops. As the superficial $F$-factor is large enough (*i.e.* larger than 4.5), it appears to exert an insignificant influence on $D_{32}$. Here, the liquid flowing to the plate is completely atomized.

### 4.2 Effect of liquid loading on $D_{32}$

Figure 6 shows a plot of $D_{32}$ on the plate liquid loading. $D_{32}$ increases gradually with the increment of liquid loading on the plate at the same hole $F$-factor. When the liquid loading is large enough (*i.e.* larger than $5\,m^3{\cdot}h^{-1}{\cdot}m^{-1}$), the dependence of $D_{32}$ on liquid loading seems slight. According to the classical atomization theory, the droplets size distribution is decided by gas or vapor momentum and liquid physical properties (mainly depending on surface tension). When the vapor hole $F$-factor is fixed, the momentum for breaking up of droplets is certain. As the liquid loading increases, the dispersion of liquid on the tray is bad. Hence, $D_{32}$ becomes large. At some constant liquid loading, the system reaches the limit of dispersion ability, so $D_{32}$ changes slightly. If the liquid loading continues to increase, weeping on the tray may take place.

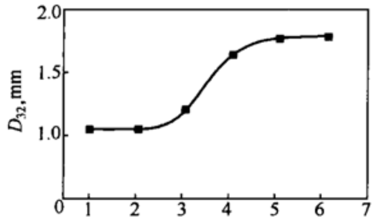

**Figure 6** Effect of liquid loading on $D_{32}$
[air-water system, $H = 50\,cm$, $F_0 = 12.5\,m{\cdot}s^{-1}{\cdot}(kg{\cdot}m^{-3})^{0.5}$]

### 4.3 Effect of radial position on $D_{32}$

Figure 7 shows a plot of $D_{32}$ at three different radial positions in the column. $D_{32}$ is not significantly affected by the radial position of the probe in the column. It shows that the droplets above the large-holed sieve tray are well distributed. This is important for the trays to operate in the spray regime. It indicates that the vapor and liquid on the large-holed compound sieve tray are well distributed.

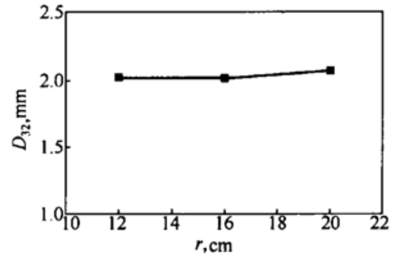

**Figure 7** Effect of radial position on $D_{32}$
[$H = 10\,cm$, $L_w = 3.1\,m^3{\cdot}h^{-1}{\cdot}m^{-1}$,
$F_0 = 14.28\,m{\cdot}s^{-1}{\cdot}(kg{\cdot}m^{-3})^{0.5}$]

### 4.4 Effect of axial position on $D_{32}$

The variation of $D_{32}$ along the axial position from the tray is shown in Fig. 8. $D_{32}$ decreases when the axial position above the tray increases. Since for the same hole F-factor, the projection velocity of small droplet is greater than that of big one, the height which small droplet can reach is higher than that of large droplet, thus $D_{32}$ decreases along the axial position.

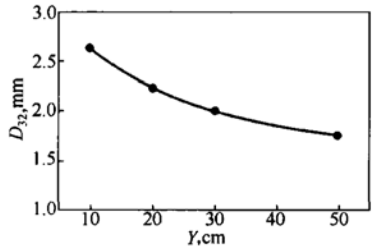

**Figure 8** Effect of axial position on $D_{32}$
($L_w = 5.1\,m^3{\cdot}h^{-1}{\cdot}m^{-1}$, $F_0 = 12.5\,kg^{1/2}{\cdot}m^{1/2}{\cdot}s^{-1}$)

### 4.5 Effect of liquid physical properties on $D_{32}$

The effect of liquid physical properties on $D_{32}$ is shown in Fig. 9 and 10. Fig. 9 indicates the relation between $D_{32}$ and viscosity of liquid, and the relation between $D_{32}$ and surface tension is shown in Fig. 10.

As shown in Fig. 9, $D_{32}$ increases with the increase of viscosity of liquid under the same operating conditions. The nature of viscosity is the intermolecular forces, the motion of molecules and collision among molecules. For the gas momentum to break up the liquid into droplets, it must overcome the intermolecular and friction forces. With the increase of viscosity, the momentum transferred to overcome the friction force will increase and the degree of liquid dispersion decreases, thus $D_{32}$ increases. In the spray regime, the stability of droplets reduces with the decrease of surface tension, *i.e.* surface tension negative system. Larger droplet is easy to be divided into smaller droplets. Hence, $D_{32}$ decreases, as shown in Fig. 10, and the interfacial area of droplets increases. Therefore, surface tension negative systems can enhance the mass transfer efficiency in the spray regime.

The effect of operating variables and physical properties on $D_{32}$ can be expressed as

$$D_{32} = 1642.06\sigma^{0.770}\mu^{0.237}F_0^{-0.965}H^{-0.277}L_{\mathrm{w}}^{0.148} \quad (1)$$

Pinczewski and Fell[2] have measured the distribution of droplet sizes on some industrial scale sieve trays whose free areas were below 16%. They represented the relationship between $D_{32}$ and hole velocity $u_0$ as follows:

$$D_{32} = 0.0315u_0^{-0.94} \quad (2)$$

Hence, relation between $D_{32}$ and hole velocity is similar in Eqs. (1) and (2).

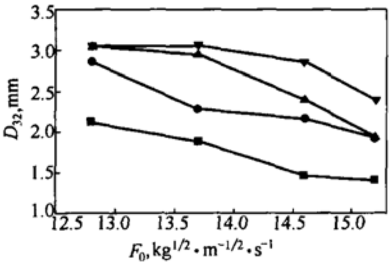

**Figure 9 Effect of viscosity on $D_{32}$**
$\mu\times10^5$, Pa·s: ■ 0.9; ● 2.3; ▲ 3.8; ▼8.5

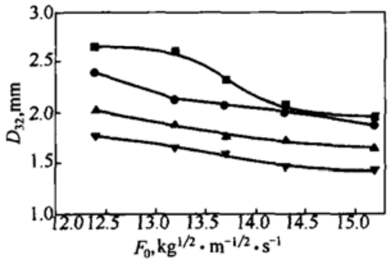

**Figure 10 Effect of surface tension on $D_{32}$**
$\sigma$, N·m$^{-1}$: ■ 0.071; ● 0.063; ▲ 0.053; ▼ 0.041

## 5 CONCLUSIONS

Droplets size and size distribution formed by the atomization of liquid on a compound sieve tray with 15 mm hole diameter and 30% free area operating in the spray regime are measured. The present results indicate that the varables, such as the hole F-factor, surface tension, liquid rate per unit weir length, and height above the sieve tray, have the influence on the Sauter mean diameter of the droplet population. However, $D_{32}$ appears to be dependent primarily on the hole F-factor of the trays and liquid surface tension.

Also, experiments indicate that the size and size distribution of high density droplets can be measured by using a double electrical probes technique, and the droplet population can be successfully represented using an upper limit logarithm distribution function.

The results in this work can afford an important proof for establishing a model of droplet motion and also the mass-transfer model in the spray regime in coming papers.

## NOMENCLATURE

| | |
|---|---|
| $C(S,T)$ | pulse total counts. In a time interval $T$, it produces $C$ drops whose diameters are equal to or greater than $S$ |
| $D$ | droplet diameter, m |
| $D_i$ | $i$ diameter of droplet |
| $D_{32}$ | the Sauter mean diameter, m |
| $F_{\mathrm{T}}$ | superficial $F$-factor ($F_{\mathrm{T}} = u_{\mathrm{T}}\sqrt{\rho_{\mathrm{G}}}$), m·s$^{-1}$(kg·m$^{-3}$)$^{0.5}$ |
| $F_0$ | hole $F$-factor ($F_0 = u_0\sqrt{\rho_{\mathrm{G}}}$), m·s$^{-1}$(kg·m$^{-3}$)$^{0.5}$ |
| $f(D)$ | probability of density function of the drop diameter $D$ |
| $H$ | height above the sieve tray, m |
| $L_{\mathrm{w}}$ | liquid rate per unit weir length, m$^3$·h$^{-1}$·m$^{-1}$ |
| $N_i$ | droplet numbers whose droplet size equal $D_i$ |
| $r$ | radial position |
| $S$ | distance between double probes, mm |
| $T$ | time, s |
| $u_{\mathrm{T}}$ | superficial velocity, m·s$^{-1}$ |
| $u_0$ | hole velocity, m·s$^{-1}$ |
| $Y$ | axial position, m |
| $\mu$ | viscosity of liquid, Pa·s |
| $\rho_{\mathrm{G}}$ | gas-phase density, kg·m$^{-3}$ |
| $\sigma$ | surface tension of liquid, N·m$^{-1}$ |

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