INFLUENCE OF SOME GEOMETRICAL PARAMETERS ON THE CHARACTERISTICS OF PREFILINGM TWIN-FLUID ATOMIZATION

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Received August 2013, Accepted May 2014  
No. 13-CSME-166, E.I.C. Accession Number 3624

ABSTRACT

Geometries are considered to have a great influence on the spray characteristics of atomizers. In the present study, we studied a prefilming twin-fluid atomizer patented by Sadatomi and Kawahara (2012), in which liquid atomization is implemented by supplying compressed air alone into an internal mixing chamber, and water is automatically sucked by the negative pressure induced by an orifice. In the experiments, we studied spray characteristics influenced by the geometrical parameters, such as orifices in different opening area ratios and different shapes, porous rings with different porous diameters, and different atomizer sizes. Higher spray performance can be obtained by a small sized atomizer with a circular orifice in opening area ratio of 0.429 and a porous fiber ring with porosity of 25 \(\mu\)m. The present results provide a significant guidance for practical applications with different requirements of spray characteristics.

Keywords: spray characteristic, twin-fluid atomizer, orifice, porous ring.

INFLUENCE DE QUELQUES PARAMÈTRES DE GÉOMÉTRIE SUR LES CARACTÉRISTIQUES DE FORMATION D’UN PREMIER FILM DANS L’ATOMISATION BI-FLUIDE

RÉSUMÉ

La géométrie est considérée comme ayant une grande influence sur les caractéristiques de pulvérisation des atomiseurs. Le sujet de notre recherche est un atomiseur bi-fluide avec formation d’un premier film breveté par Sadatomi and Kawahara (2012) dans lequel l’atomisation du liquide est réalisée par l’apport d’air comprimé seul dans la chambre de mélange interne, l’eau est automatiquement aspiré par la pression négative induite par un orifice. Au cours de l’expérimentation, nous avons étudié les caractéristiques de pulvérisation influencées par les paramètres géométriques, tels que des orifices dans des ratios d’ouvertures différents et de différentes formes, des zones poreuses avec les diamètres des pores différents et de tailles différentes. Des performances plus élevées de pulvérisation peuvent obtenues par un petit atomiseur avec un orifice circulaire d’un ratio d’ouverture de 0.429 et un anneau de fibres poreuses de 25 \(\mu\)m. Les résultats fournissent des données significatives dans l’orientation vers des applications pratiques exigeant des caractéristiques de pulvérisation différentes.

Mots-clés : caractéristiques de pulvérisation; atomiseur bi-fluide; orifice; anneau poreux.
1. INTRODUCTION

Atomization is the breakup of a liquid mass into small droplets, and the aggregate of all drops formed is referred to as a “spray”. Rayleigh in 1878 [1] was the first to study theoretically the breakup of liquid jets and explained the theoretical mechanism of droplet generation, as described in Fig. 1. The existing model, whose exactitude seems to be confirmed by scientific research, considers that the liquid flowing through the nozzle and passing the orifice edge evolves into a liquid sheet or liquid column. This liquid sheet or column, due to instability induced by aerodynamic forces, breaks up first into membrane or elongated ligaments more or less cylindrical, and later into droplets. These processes determine the shape, structure, and penetration of the resulting spray as well as its detailed characteristics of droplet velocity and drop size distribution [2]. Meanwhile, these processes are strongly affected by nozzle size and geometry, the physical properties of the liquid, and the properties of the gaseous medium into which the liquid stream is discharged [3].

Based on the above principle of liquid atomization, various kinds of atomizers were invented and studied. Lefebvre [4] classified the existed atomizers as plain-orifice, simplex, dual-orifice, spinning disc, airblast and effervescent. In these types, airblast and effervescent atomizers are twin-fluid atomizers, which employ the kinetic energy of a flowing air-stream to shatter a liquid jet or sheet into ligaments and then drops. The relative velocity required to promote the interaction between the liquid surface and the co-flowing air is given by the high-velocity air. To complete the reversal of roles played by the air and the liquid in twin-fluid atomization, the liquid is injected into the atomizing air at low velocity. In fact, it is highly desirable that the liquid velocity should be kept as low as possible in order to maximize the relative velocity between the liquid and the atomizing air [5].

In internal-mixing twin-fluid atomizers, especially when operating at high air-liquid ratios, primary atomization occurs either just upstream of the discharge orifice or in the orifice itself. Further droplet breakup (secondary atomization) occurs downstream of the nozzle exit, in the region where the nozzle efflux first
encounters the surrounding air [3]. So the final range of drop sizes produced in a spray depends not only on the drop sizes produced in primary atomization but also on the extent to which these drops are further disintegrated during secondary atomization [2].

Lefebvre and his team obtained series of important achievements on twin-fluid atomizers and proved that twin-fluid atomizers have many advantages over other types of atomizers, since they require lower pump pressures and produce a finer spray [4]. The applications of twin-fluid atomizer are focused on engine combustion [6, 7], humidification [8], gas cooling [9], spray painting [10] and spray drying [11], etc.

Several methods are employed to achieve atomization in twin-fluid atomizers. Some employ the pressure principle, where the liquid is supplied from a pressurized source [12]; others use the gravity principle, where the liquid supply is located above the nozzle, invoking gravity for the liquid flow; the siphon principle is also used in some twin-fluid atomizers, where the liquid source is self-aspirating [13].

In order to utilize the liquid-siphoning principle and minimize the drop size in the primary atomization, Sadatomi and Kawahara [14] patented a large-flow-rate and high-efficiency prefilming twin-fluid atomizer with orifice and porous ring as described in Fig. 2. This atomizer is composed of six parts: main body, water suction pipe, inlet, orifice, porous pipe, and outlet (outlet can also be regarded as internal mixing chamber in this atomizer). All the parts are easy to manufacture because of its simple structure, e.g. the inlet and outlet are straight cylindrical pipes, the orifice and porous pipe are cut-off and assembled easily [15]. The siphon principle is adopted in this atomizer, so the working process is as follows: compressed air is fed through
the inlet (with velocity $v_{G1}$, pressure $p_{G1}$), then water is sucked automatically into the air-flow through the porous pipe by the vacuum pressure ($p_{G2}$) arising just behind the orifice. With the increase in air velocity ($v_{G2}$), air and water interact with each other in the internal mixing chamber, and mist is formed and sprayed through the outlet.

In this paper, experimental study was conducted for the following three purposes:

1. Clarify the influence of orifice geometries on spray characteristics. The orifice set in the middle of the atomizer is used to induce vacuum pressure, in order to suck water without water pump. Considering the importance of the orifice, different diameters and shapes of the orifice were tested.

2. Study the influence of prefilming diameter caused by different porous materials on drop size. The porous ring with numerous tiny holes is used as a prefilming function to form liquid ligaments undergoing further disintegration during the process of water suction, in order to generate smaller droplets in high efficiency [16]. Two kinds of porous rings are tested: porous fiber and porous sheet.

3. Study the influence of atomizer size on spray performance. The spray performance of the two sizes of atomizers is compared, in order to study the influence of the size on the spray performance and clarify the scaling possibility of the atomizer.

Finally, typical applications of the present atomizer are described.

2. DESCRIPTION OF THE EXPERIMENTS AND METHODS

2.1. Overall Apparatus for Hydraulic Performance Test

The overall experimental apparatus for the hydraulic performance test is shown in Fig. 3. Two bold lines are connected to the atomizer nozzle, one line from an air compressor, and the other line sucks water from a water tank. The level of water surface in the tank is the same as that of the water suction port of the atomizer to eliminate the influence of level difference. Three more fine lines are connected to an A/D converter, the output signals from the flow rate and two pressure sensors. The data via the A/D converter are processed by a computer.

Drop size distributions are often described by some characteristic diameters given by Eq. (1):

$$d_{ab} = \left[ \frac{\sum i n_i d_i^a}{\sum i n_i d_i^b} \right]^{1/(a-b)}.$$  \hspace{1cm} (1)

Here, $i$ denotes the number of droplet size range, $n_i$ is the number of droplets in the size range $i$, and $d_i$ is the diameter of the size range $i$; $a$ and $b$ are integers defining a particular characteristic diameter. For example, $d_{10}$ is the arithmetic mean diameter of all sprayed drops; $d_{32}$, the Sauter mean droplet diameter, is often of use in applications where the surface area is important (e.g. gas absorption, air cooling) [17]. In the present study, $d_{10}$ and $d_{32}$ are used to identify the spray quality.

2.2. Orifices in Different Diameters and Shapes

Orifice (i.e. a thin plate with a hole in the center) is mainly used for flow rate measurement in fluid delivery systems since its simple structure and reliable performance [18], and different orifice diameters induce different pressure drops [19]. In this study, such an orifice is adopted for inducing negative pressure downstream from it in the atomizer to suck water. Thus, the orifice in different bore diameter induces different negative pressure and leads to different spray performance.

We define the cross-sectional area ratio of the orifice to pipe, $\beta^2$, by

$$\beta^2 = \frac{A_o}{A_D}.$$  \hspace{1cm} (2)
Table 1 lists the present atomizers with different orifice and mixing chamber diameters. LO, MO and SO refer to large, middle and small sized orifice-type atomizer, respectively. The number following O is the orifice diameter/the chamber diameter. Large sized atomizers with different orifice diameters were tested to clarify the influence of the opening area ratio of the orifice to the mixing chamber on the spray performance. Moreover, Aly et al. [20] experimentally studied fractal-shaped orifices in a pipe flow and showed that the orifices in fractal geometries generate various velocity scales including more mixing and causing the flow to form a series of jets, which improves the pressure recovery and decreases the absolute pressure drop. Likewise, for an atomizer, more disturbances in the mixing chamber cause more mixing between air and water, resulting in finer droplet spray. Thus, three types of orifices in different fractal shapes but with the same flow area as the small sized atomizer (Table 2) were tested, and a comparison among them was made to clarify the influence of orifice geometries on the spray characteristics.

2.3. Porous Rings with Different Materials
One of the predominant factors affecting liquid disintegration by the present atomizer is the hole diameter of the porous ring, since the final drop size is determined by two steps: primary atomization (liquid column coming from the porous ring) and secondary atomization (breakup of droplets or liquid ligaments in the mixing chamber). Thus, as listed in Table 3, two types of porous rings with different materials were tested to clarify the influence of the hole diameter on the drop size. The porous fiber ring was made from a commercial porous pipe (MF-I FILTER with 25 \(\mu\)m in porosity, produced by Asahi Fiber Industry CO.,

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Table 1. Different orifices with circular hole and chamber diameters in the present atomizers.

<table>
<thead>
<tr>
<th>Name</th>
<th>Orifice diameter (d_o) [mm]</th>
<th>Chamber diameter (D) [mm]</th>
<th>Area ratio (\beta^2) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO-12.5/21</td>
<td>12.5</td>
<td>21</td>
<td>0.354</td>
</tr>
<tr>
<td>LO-13.8/21</td>
<td>13.8</td>
<td>21</td>
<td>0.429</td>
</tr>
<tr>
<td>LO-14.6/21</td>
<td>14.6</td>
<td>21</td>
<td>0.482</td>
</tr>
<tr>
<td>MO-9.16/14</td>
<td>9.16</td>
<td>14</td>
<td>0.429</td>
</tr>
<tr>
<td>SO-4.58/7</td>
<td>4.58</td>
<td>7</td>
<td>0.429</td>
</tr>
</tbody>
</table>
Table 2. Orifices in different geometries but same area ratio of 0.429 (4-Notch and 8-Notch-orifice have the equivalent circular area with Circular orifice).

<table>
<thead>
<tr>
<th>Name</th>
<th>Geometry</th>
<th>(d_0) [mm]</th>
<th>(D) [mm]</th>
<th>Depth of notch [mm]</th>
<th>Notch angle [°]</th>
<th>(A_0) [mm²]</th>
<th>Area ratio (\beta^2) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td></td>
<td>4.58</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>16.47</td>
<td>0.429</td>
</tr>
<tr>
<td>4-Notch</td>
<td></td>
<td>4.18</td>
<td>7</td>
<td>0.71</td>
<td>60</td>
<td>16.47</td>
<td>0.429</td>
</tr>
<tr>
<td>8-Notch</td>
<td></td>
<td>3.74</td>
<td>7</td>
<td>0.71</td>
<td>60</td>
<td>16.47</td>
<td>0.429</td>
</tr>
</tbody>
</table>

Table 3. Porous rings with different materials.

<table>
<thead>
<tr>
<th>Name</th>
<th>Photograph</th>
<th>Thickness [mm]</th>
<th>Porosity or hole diameter [μm]</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous fiber</td>
<td>Overview</td>
<td>1.5</td>
<td>25</td>
<td>Polyolefin fiber</td>
</tr>
<tr>
<td>Porous sheet</td>
<td>Macro</td>
<td>0.15</td>
<td>125</td>
<td>Stainless metal</td>
</tr>
</tbody>
</table>

Japan), and the thickness was 1.5 mm. The porous sheet ring, on the other side, was made of stainless metal sheet with a thickness of 0.15 mm and a huge number of 125 μm diameter holes. The inner diameters of the two porous rings were the same, depending on the chamber diameter as listed in Table 1. The water suction length of these rings was fixed at 8 mm independent of both the porous material and the porous inner diameter.

2.4. Two Sizes of Atomizers
The size of an atomizer is considered to have an influence on the spray performance. Jicha et al. [21] proved that smaller diameter mixing chamber contributes to a more stable spray; however, other spray effects influenced by the sizes were not tested so far. As a consequence, two types of atomizers with the same linear scale listed in Table 4 were developed to test size influence. Though the chamber length of 44.5 mm for the middle sized atomizer is a little longer than twice of 20.5 mm for the small sized one, the middle sized one with 44.5 mm chamber length showed the best performance than those with different chamber lengths.

3. RESULTS AND DISCUSSIONS
The experimental results are shown and discussed in the following steps:

1. Influence of the opening area ratio of orifice to mixing chamber on the spray performance.
2. Influence of orifice geometries at the optimized area ratio in step 1.
3. Influence of porous ring materials at the optimized one in steps 1 and 2.
4. Influence of the atomizer size at the optimized proportion.
Table 4. Two sizes of atomizers in the same linear scale.

<table>
<thead>
<tr>
<th>Name</th>
<th>Orifice diameter $d_0$ [mm]</th>
<th>Chamber diameter $D$ [mm]</th>
<th>Area ratio $\beta^2$ [-]</th>
<th>Chamber length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO-4.58/7</td>
<td>4.58</td>
<td>7</td>
<td>0.429</td>
<td>20.5</td>
</tr>
<tr>
<td>MO-9.16/7</td>
<td>9.16</td>
<td>14</td>
<td>0.429</td>
<td>44.5</td>
</tr>
</tbody>
</table>

Fig. 4. Comparison of water suction performance against gas volume flow rate between three atomizers with different opening area ratios.

3.1. Influence of Orifice Opening Area Ratio on Spray Characteristics

In Fig. 4, the experimental data on the atomized liquid volume flow rate ($Q_L$) is for the large sized atomizer where the porous ring of PF is plotted against the gas volume flow rate supplied ($Q_G$) for three atomizers with different orifice opening area ratios. Since the liquid flow rate depends on the negative pressure induced by the presence of orifice, the liquid volume flow rate increases with increasing of air flow rate. Among these three atomizers, LO-13.8/21-PF with the medium opening area ratio, $\beta^2$, showed the largest $Q_L$. The reason is as follows. At a fixed $Q_G$, the air velocity at the orifice ($v_{G2}$) at the lowest $\beta^2$ becomes highest, and the absolute value of the negative pressure at the vena contracta becomes highest. However, the region of negative pressure around the vena contracta becomes narrow than the length of the porous ring, because the vena contracta is closer than necessary [22]. Contrary to this, $v_{G2}$ at the highest $\beta^2$ becomes lowest, and the negative pressure as well as $Q_L$ become lowest.

From an economical point of view, the mist generation efficiency calculated by Eqs. (3) and (4) [23] shows that the higher it is, the better it would be.

\[
L_G = \left( p_{G1} + \frac{\rho_{G1}}{2} v_{G1}^2 \right) Q_G, \tag{3}
\]

\[
\eta_M = \left( \frac{\rho_L Q_L v_{G1}^2}{2} \right) L_G. \tag{4}
\]

Here, $Q_G$ is the gas volume flow rate under the standard conditions, and $L_G$ is the pneumatic power consumed by the atomizer. In addition, the velocity of mist in Eq. (4) is taken to be the same as that of air.

The efficiency ($\eta_M$) of the three atomizers with different opening area ratios was studied at various gas volume flow rates ($Q_G$) in Fig. 5. The efficiency increases as the gas volume flow rate increases, irrespec-
Fig. 5. Comparison of atomization efficiency against gas volume flow rate among three atomizers with different opening area ratios.

Fig. 6. Diameter distribution of droplets by the large sized atomizer with different opening area ratios.

tive of the opening area ratio. Among these atomizers, LO-13.8/21-PF type showed the highest efficiency corresponding to the experimental results in Fig. 4, though the efficiencies of the three become closer with the increase of gas volume flow rate. Thus, the atomizer with the opening area ratio of 0.429 is superior to others.

Figure 6 compares the percentages of droplet diameter distribution data for the three atomizers at $v_{G1} = 180$ m/s and $Q_L = 0.2$ l/min. About 92% of droplets were smaller than 10 µm in diameter for LO-13.8/21-PF type orifice, which is better than the other two types. This is probably due to the proper orifice area ratio inducing a more stable air-water interaction in the mixing chamber.

As a summary, the spray characteristics are influenced greatly by the orifice opening area ratio. Among the three orifices, the atomizer with LO-13.8/21-PF with the opening area ratio of 0.429 showed the best spray performance, i.e., higher water suction ability, higher atomization efficiency and better droplet diameter distribution.
3.2. Influence of Orifice Geometries

The orifice with the opening area ratio of 0.429 showed the best performance in the present atomizer as described in the last section, thus three orifices in different geometries but the same opening area ratio of 0.429 were tested.

Figure 7 shows the water suction pressure at inlet ($p_{Lin}$). The pressures are negative and decrease gradually as the gas volume flow rate ($Q_G$) increases, and the atomizers with the fractal orifices (4-Notch and 8-Notch) have a similar feature. The circular orifice induces stronger negative pressure than the fractal orifices in all gas flow rate conditions, which is attributed to the less pressure loss produced by the circular orifice than the fractal orifices [20].

In Fig. 8, the experimental data on the Sauter mean diameters ($d_{32}$) of droplets for three atomizers with different orifice geometries are plotted against the liquid flow rate at a fixed gas volume flow rate of $Q_G = 180$ l/min. The Sauter mean diameter becomes larger as the gas/liquid flow rate ratio decreases, as reported
by many investigators, such as in [24–26]. The atomizer with 4-Notch orifice gave smaller $d_{32}$ than the other two, irrespective of $Q_L$, because the 4-Notch orifice induces stronger turbulence or mixing in the mixing chamber than others [20]. On this point, employing a fractal-shaped orifice is an effective way to improve liquid atomization quality. However, the atomizers with 4-Notch and Circular orifices take similar $d_{32}$ in a larger liquid flow rate (i.e. low gas/liquid flow rate ratio) condition.

3.3. Influence of Porous Ring Materials

Liquid flow rate ($Q_L$) data for the atomizer with different porous rings are plotted against the mean gas velocity ($v_{G1}$) at the atomizer inlet in Fig. 9. The two curves corresponding to the two atomizers show a similar trend, namely, the liquid flow rate increases with the increase in the gas velocity. This is attributed to the stronger negative pressure induced by the higher gas velocity. In addition, the atomizer with the porous sheet ring gives higher water suction performance than that with the porous fiber ring, since the hole diameter of the porous sheet is much larger than that of the porous fiber. The resistance for water suction depends on the hole diameter.

The Sauter mean droplet diameter ($d_{32}$) data for the two porous ring types were plotted against the gas velocity at two different liquid flow rates in Fig. 10. At a fixed liquid flow rate, the Sauter mean droplet diameter decreases with increase in the gas velocity. At a fixed gas velocity, the Sauter mean droplet diameter increases with the increase in the liquid volume flow rate. Such a regularity was also reported by Lefebvre [27]. The smaller Sauter mean droplet diameter for the porous fiber type is attributed to the smaller liquid prefilming in the porous fiber [5].

In addition, the Sauter mean droplet diameter for the porous fiber type was similar to that obtained by Barreras et al. [28] for industrial twin-fluid atomizers. This means that the present atomizer can be applied to industrial purposes.

3.4. Influence of Atomizer Size

Two sized atomizers with porous fiber rings were tested to study the influence of the atomizer size on the spray characteristics. The results are shown in Figs. 11 and 12.

Figure 11 compares the liquid suction rate, $Q_L$, of different sized atomizers against the pneumatic power consumption, $L_G$. The gradients of two curves decrease with increase in pneumatic power, which means
that the more the energy supply, the more is the power loss. Although the middle sized atomizer gives twice mist flow rate of the small sized one, it consumes about 10 times energy of the latter. Thus, if say, 1.2 l/min of mist generation rate is required, double use of the small sized one is recommended from an energy saving point of view, because the power consumption can be reduced to one-fifth.

The atomization efficiencies of different sized atomizers are compared in Fig. 12. The efficiency of each atomizer increases with increasing inlet gas velocity, $v_{G1}$. In addition, the efficiency of the middle sized atomizer is much lower than that of small size. This suggests that we should choose the smaller sized one even if a large mist flow rate is required.

Table 5 compares the droplets diameters between two different sized atomizers at $v_{G1} = 103$ m/s and $v_{L1} = 0.034$ m/s. The $d_{32}$ and $d_{10}$ of the two sized atomizers are quite similar, which means the drop size is little influenced by the atomizer size. However, Elshanawany and Lefebvre [25] experimentally clarified that except for the influence of gas and liquid velocity, the drop size for the prefilming airblast atomizers.
is also influenced by the atomizer size, and it increased according to about 0.43 power of the atomizer size. The reason for inconsistency in data between the present atomizer and their airblast atomizers is as follows: The drop size for the airblast atomizers depends on the thickness of the pre-filming liquid sheet or the diameter of the ligament. For the present atomizer, however, the same porous fiber with the porosity of 25 µm was used independent of the atomizer size, and was little influenced by the atomizer size. Combining with Elshanawany and Lefebvre’s [25] results, we can conclude that the drop size for a general prefilming atomizer is predominantly influenced by the prefilming diameter of liquid sheet or ligament, and the reduction of the prefilming part size of the atomizer is another effective way to improve the atomization quality.

4. CONCLUSIONS

Experiments were conducted to study the influence of atomizer parameters on spray characteristics of a prefilming twin-fluid atomizer patented by Sadatomi and Kawahara [14]. The influence of some parameters was studied. The results are summarized as follows:

1. The atomizer with different orifice opening area ratios (0.359, 0.429, 0.482) was tested. Among the three, LO-13.8/21-PF with the area ratio of 0.429 showed the highest water suction performance, the highest atomization efficiency and the smallest drop size.

2. The atomizer with different orifice geometries but the same orifice area ratio of 0.429 was tested. The atomizer with circular orifice showed the highest water suction performance than those with the fractal orifices; nevertheless, that with the fractal orifice with four notches showed the best liquid disintegration effect (i.e. smallest Sauter mean droplet diameter). Thus, employing a fractal-shaped orifice is an effective way to improve the liquid atomization quality.
3. The atomizer with different porous materials was tested. The atomizer with the porous fiber could generate a much smaller droplet than the one with the porous sheet due to its smaller liquid prefilming, though the atomizer with the porous sheet gave a larger water suction performance. Thus the selection of porous ring must be determined by practical applications with specified requirements.

4. Two differently sized atomizers with the same proportion were tested. The small sized atomizer showed the mist generation rate half of the middle-sized one but had a much higher atomization efficiency. The drop size was not influenced by the atomizer size. It is better to use the small sized atomizer, even double or multi-use if necessary from a viewpoint of saving energy.

For the practical significance, the atomizer with the optimum specifications in the present study is effective against CO$_2$ capture in a closed room [29], air cooling in greenhouse [16], humidification in living room, etc.

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to Mr. K. Tanaka, student at Kumamoto University, Mr. M. Tsuji and E. Sakurai, working in Kawasaki Heavy Industries, LTD, for their experimental cooperation. Appreciation is also for the Chinese Government for the scholarship to Mr. Jiafeng Yao.

REFERENCES