AIR PURIFICATION USING MISTS GENERATED BY AN EFFICIENT MULTI-FLUID MIXER

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ABSTRACT

Sadatomi and Kawahara developed an efficient, i.e., energy-saving-type, multi-fluid mixer, which can generate mists (or micro-bubbles) by introducing pressurized air (or water) alone because water (or air) as a source of mists (or micro-bubbles) are automatically sucked by a vacuum pressure arisen inside the mixer. In the present paper, firstly, the hydraulic performance of the mixer in mists generation case is introduced by referring to our previous papers. Secondly, various applications of mists, such as air cooling in greenhouses and pigsty, adsorptions of black smoke in the chimney of a boiler burning Refuse Paper & Plastic Fuel (RPF), and adsorption of carbon dioxide (CO_2) in room are described. In the CO_2 adsorption tests, mists were sprayed for five minutes by our multi-fluid mixer, commercial single-fluid and twin-fluid atomizers in turn in a test room, and time variations of CO_2 concentration in air after the introduction of CO_2 in the room were measured at the bottom of the room to compare the CO_2 adsorption rates for the respective cases. In addition, diameters of droplets captured in a small oil pond were measured with a microscope. As a result, superiority of our multi-fluid mixer was confirmed, because 40% droplets were 20 to 40 μm in diameter, and the CO_2 adsorption rate by the mists with our multi-fluid mixer was 25 % larger than that with the commercial ones.

INTRODUCTION

Atomizing nozzles or atomizers are categorized as single-fluid type, twin-fluid type and special types with rotating disc, vibrating plate, etc. [1]. Of these, the twin-fluid type is usually employed if one must spray a large amount of fine liquid droplets smaller than 100 μm [1]. However, the twin-fluid type has a demerit because two pressurizers respectively for water and air must be prepared, and the total cost of equipment and electricity is higher than that for the single-fluid type.

Sadatomi and Kawahara invented a multi-fluid mixer shown in Figure 1 [2] which is categorized as a twin-fluid type which has a merit because water is automatically sucked through a porous pipe by a negative pressure arisen downstream from an orifice in the mixer. Thus, the mixer can be operated with lower electric power than the usual twin-fluid type, i.e., operable with a solar power [3-8]. The mixer is also usable as micro bubble generator [9, 10] when water is supplied and air is sucked. In our previous studies [4-8], better geometrical parameters were discussed and explained, i.e., the diameter ratio of the orifice to the mixer pipe, the ratio of outlet length from the rear end of the porous pipe to the mixer pipe diameter, the geometry of the orifice, the whole size, and the CO_2 adsorption performance by the mists as a trial test.

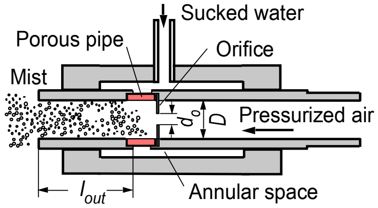


Figure 1 Twin-fluid atomizer patented by Sadatomi and Kawahara [2]

The purpose of the present study is to compare the above twin-fluid type with commercial single-swirl and twin-fluid types on the spray performance and the CO_2 adsorption performance with the mists. In the present paper, firstly, some findings in our previous studies [3, 4] have been described for our twin-fluid type mixer. Secondly, the present experimental results on the hydraulic performance together with the CO_2 adsorption performance by the mist with the three atomizers have been described.

NOMENCLATURE

d_o	[m]	Orifice diameter
D	[m]	Mixing chamber diameter
l_{out}	[m]	Mixing chamber length
L_G	[W]	Pneumatic power
P	[Pa]	Gauge pressure
Q	[m^3/s]	Volume flow rate
t	[s]	Time
v	[m/s]	Cross-sectional average velocity

Special characters

β^2	[-]	Opening area ratio of orifice
η	[-]	Energy transfer efficiency to water
ρ	[kg/m^3]	Density
ζ	[-]	Pressure loss coefficient

Subscripts

G	Gas phase
GO	Gas phase at atmospheric condition
H	Homogeneous mixture of gas and liquid
L	Liquid phase
1, 2, 3	Positions

EXPERIMENT

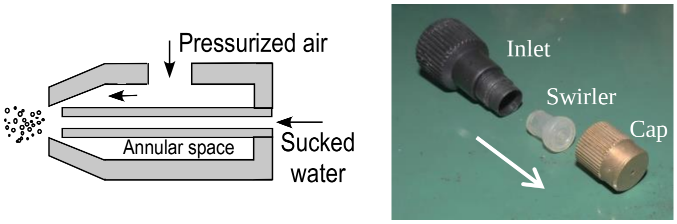
Test Atomizers

Three atomizers of L, M and S in our twin-fluid type were tested in order to study the size effects [7]. The pipe and orifice diameters of S type were 7 and 4.58 mm respectively as listed in Table 1, and the outlet length was 20.5 mm, and fiber porous pipe was 25 μm in porosity and 1.5 mm in thickness. The M type and the L type were twice and three times larger than the S type besides the porosity and the thickness of the porous pipe. Of these, the S type was the most efficient, i.e., the highest in the spray rate to the pneumatic power required [7]. In addition, the proportion of the mixer, such as ratio of the orifice to the pipe diameter and ratio of the outlet length to the pipe diameter, was optimized so as to give the best performance [4-6].

Figures 2 (a) and (b) show the commercial atomizers tested respectively for a twin-fluid MMA100 for atomizing fine mists (Kyoritsu Gokin Co., Japan) and a single-fluid swirl type for gardening use (Maruhachi Industrials Type Co., Japan). The twin-fluid MMA100 can spray without water power because the air pressure near the atomizer outlet becomes negative. The single-fluid swirler is composed from a 7 mm I. D. water inlet, a swirler, and a cap with 0.7 mm orifice. The inlet diameter is the same as that of the twin-fluid S type.

Table 1 Specifications of twin-fluid type atomizers tested

Name	Pipe dia. D mm	Orifice dia. d_o mm	Orifice opening area ratio, $(d_o/D)^2$
L type	21	13.8	0.429
M type	14	9.16	0.429
S type	7	4.58	0.429



(a) Twin-fluid MMA100 (b) Single-fluid swirl type

Figure 2 Commercial atomizers tested

Spray Performance

Figure 3 shows the test apparatus for the twin-fluid type atomizer [4-7]. Air was supplied with a compressor after controlling the volume flow rate, Q_G, and the gauge pressure at the atomizer inlet, P_{G1}. The volume flow rate and the pressure were measured with calibrated sensors and a data acquisition system. The accuracy of Q_G was evaluated as within 2 % from a calibration curve in our preliminary test. The pneumatic power required for the mist generation, L_G, was obtained by substituting the above measured data into

$$L_G = \left(P_{G1} + \rho_G v_{G1}^{\,2}/2\right) Q_{G1} . \tag{1}$$

Here, ρ_G and v_{G1} are the air density and the mean air velocity respectively at the atomizer inlet. However, no power was required to introduce water, because water was automatically sucked from a water tank whose water level was the same as the water inlet of the atomizer. The water flow rate, Q_L, adjusted with a valve was measured with a calibrated turbine flow meter within 1 %.

In the single-fluid swirl type test, air supply line and water supply line in Figure 3 was replaced by a water supply line connected to the atomizer top from a high pressure pump. The valve in the water line was used to control the volume flow rate, Q_L, and the gauge pressure at the atomizer inlet, P_{L1}. The hydraulic power needed for the mist generation, L_L, was obtained by substituting the data into

$$L_L = \left(P_{L1} + \rho_L v_{L1}^{\,2}/2\right) Q_L . \tag{2}$$

Here, v_{L1} is the mean water velocities at the atomizer inlet.

Furthermore, mist droplet diameter was measured with an oil pond method. In the method, the droplets were captured momentarily by opening a shutter covering the inlet of the oil pond 0.2 m below the atomizer exit, and the diameters of the droplets in the pond was measured with a digital micro-scope and an image processing system. Spray angle was measured with a picture and the radial distribution of mist flow rate 0.50 m below the atomizer exit. The distribution was determined by collecting the droplets with a lot of test tubes square arrayed.

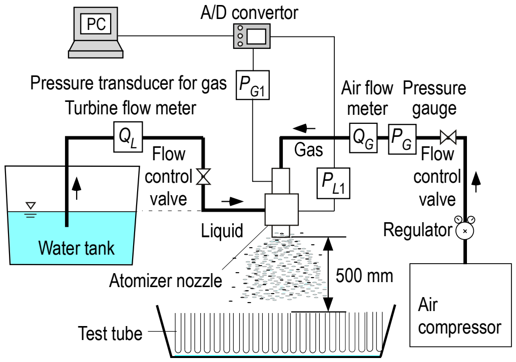


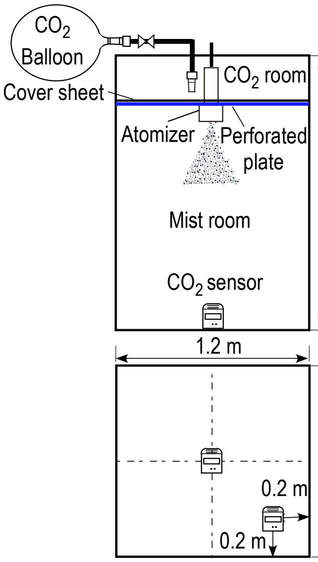
Figure 3 Test apparatus of spray performance for the twin-fluid type atomizer

CO$_2$ Adsorption Performance with Mist

Figure 4(a) and (b) show the test room of CO$_2$ adsorption by the mist, having 1.2 m in width and depth and 2.0 m in height. A perforated plate with a cover sheet was placed 1.8 m above from the bottom, and divided the room into the CO$_2$ room and the mist room. The atomizer was placed at the centre of the plate. CO$_2$ concentration in air in the mist room was detected by two sensors placed at the bottom. The procedure of the CO$_2$

adsorption test was as follows: Firstly, 1.5 l of CO_2 at standard condition was filled in a balloon placed outside the CO_2 room. Secondly, the mist was sprayed five minutes in the mist room, three minutes after the spray start the CO_2 in the balloon was released to the CO_2 room for two minutes for full diffusion. Thirdly, the spray was stopped, and CO_2 began to flow down through the perforated plate by removing the cover sheet. At the same time, CO_2 concentrations at the bottom of the mist room were measured every 5 seconds for 10 minutes. In order to know the effects of the mist spray, a similar measurement with no mist spray was also conducted.

(a) Picture of test room



(b) Sketch of apparatus

Figure 4 Test room for the CO_2 adsorption by mists

PREDICTION OF SPRAY RATE OF TWIN-FLUID TYPE

Simple Mathematical Model [4]

Spray rate, Q_L, for a given air supply rate, Q_G, can be obtained by simultaneously solving the following conservation equations of energy for the respective two points 1 and 2, 2 and 3, and 4 and 2 in Figure 5:

$$P_{G1} + \frac{\rho_G v_{G1}^{\ 2}}{2} = P_{G2} + \frac{\rho_G v_{G2}^{\ 2}}{2} + \zeta_1 \frac{\rho_G v_{G1}^{\ 2}}{2} \ , \tag{3}$$

$$P_{G2} + \frac{\rho_G v_{G2}^{\ 2}}{2} = P_{G3} + \zeta_2 \frac{\rho_H v_H^{\ 2}}{2} \ , \tag{4}$$

$$P_{G2} + \frac{\rho_L v_{L2}^{\ 2}}{2} = P_A - \zeta_3 \frac{\rho_L v_{L2}^{\ 2}}{2} \ . \tag{5}$$

Here, the point 1 is the air inlet of the atomizer, the point 2 just downstream from the orifice, the point 3 far downstream from the exit where the velocities of air and the atomized water becomes zero, the point 4 far upstream from water inlet where the gauge pressure and the velocity of water sucked are zero. P, v and ρ are the gauge pressure, the mean velocity and the density, respectively. ζ is the energy loss coefficient between the respective two points, and could be determined as ζ_1 = 1.19, ζ_2 = 1.76 and ζ_3 = 16.5 for the S type atomizer from a preliminary test.

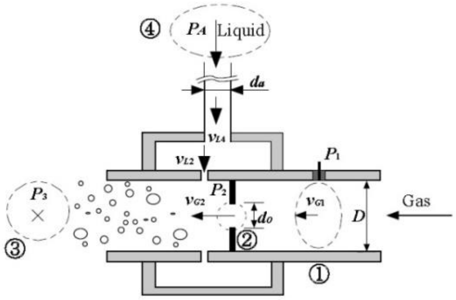


Figure 5 Explanatory diagram of the model

Since air and atomized water mixture downstream from the orifice can be regarded as homogeneous mixture, their density and velocity in the r. h. s. of equation (4) are given as:

$$\rho_H = \frac{\rho_G Q_G + \rho_L Q_L}{Q_G + Q_L} \ , \ v_H = \frac{Q_G + Q_L}{\pi D^2 / 4} \ . \tag{6}$$

In equation (5), the pressure drop through water line of d_a = 8 mm tube is assumed to be negligible in comparison with that through the porous pipe of 25 μm in porosity. If air is assumed to be incompressible, equation (7) holds:

$$Q_G = \frac{\pi}{4} d_o^{\ 2} v_{G2} = \frac{\pi}{4} D^2 v_{G1} \ . \tag{7}$$

Finally, the spray rate, Q_L, can be calculated by substituting the solutions of v_{L2} into:

$$Q_L = \frac{\pi}{4} d_o^{\ 2} v_{L2} \ . \tag{8}$$

Validation of Mathematical Model [4]

The above model was validated against the S type atomizer data on the spray rate in Figure 6 and the air inlet pressure in Figure 7. The abscissa of both figures is the air supply rate to the atomizer. Since the agreement between the calculation and the experiment is acceptable, the model is useful to predict the air supply rate and the air pressure from the air source for a prescribed spray rate, and enable the selection of air source.

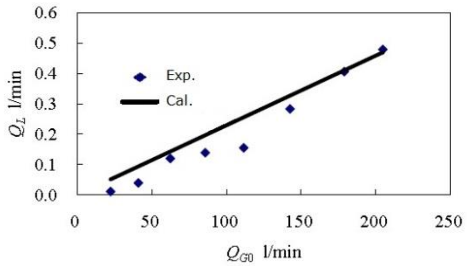


Figure 6 Comparison of Q_L between calculation and experiment

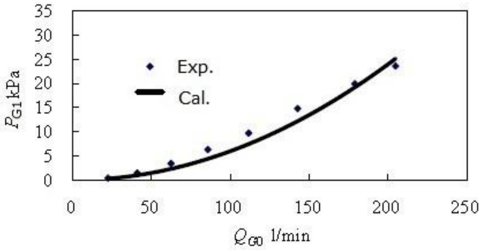


Figure 7 Comparison of P_{G1} between calculation and experiment

PRACTICAL APPLICATIONS

Our concern is the development of ecological spray systems which can produce a great deal of finer droplets around 20 μm in diameter with a low power supply such as solar cells. The industrial applications of such a system are an evaporative cooling of fine droplets in greenhouses [3], baby pig and cow houses in summer, and adsorptions of smoke and fuel gas emitted from combustors, etc.

Figure 8 Evaporative cooling of a baby pig in Kumamoto Prefecture broadcasted by TBS TV, Japan

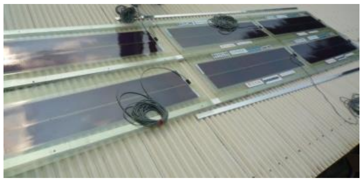


Figure 9 450 W solar cell on the roof of the pig house

Figures 8 and 9 show an evaporative cooling of a baby pig house and a solar cell on the roof of the house in Kumamoto Prefecture, which was broadcasted by Tokyo Broadcasting System Television. In the cooling system, a high pressure type blower was driven with the electricity from the 450 W solar cells, and pressurised air together with water at atmospheric pressure was supplied to the multi-fluid mixers in order to supply fine droplets in the house. Since high temperature in the house causes the loss of appetite and poor growth of the baby pigs, the cooling in summer without commercial electricity is quite ecological.

Adsorptions of black smoke in the chimney from a furnace burning Refuse Paper & Plastic Fuel (RPF) were tested by use of our spray system in a local boiler maker in Oita prefecture. Figures 10 (a) to (c) show the pictures of the original boiler system with a RPF (Refuse Paper & Plastics) stock in front, RPF and a blower for air supply to furnace. In the original system, four cyclone separators were inserted in series between the outlet of the furnace and the chimney, but black smoke was still emitted due to incomplete combustion and to poor cyclone separators performance as shown in Fig. 11(a).

(a) Boiler system with RPF stock (b) RPF

(c) Blower for air supply

Figure 10 Original boiler systems in Oita Prefecture

(a) Before revision (b) After revision

Figure 11 Black smoke removal by atomized droplets, etc.

The boiler maker asked us to find an economical method to remove the black smoke. According to our advice, the maker took off the three separator from five in order to reduce the pressure drop between the furnace outlet and the chimney, and add one more blower in series at the inlet of the original blower in order to supply more air to the furnace for better combustion, and inserted our spray system into the smoke pass in order to adsorb finer smoke dust. As a result, the smoke could be cleaned up as shown in Figure 11(b).

COMPARISON OF PERFORMANCE BETWEEN TWIN-FLUID TYPE AND SINGLE-FLUID TYPE

Spray Performance

Figure 12 compares the maximum mist flowrate, Q_L, among the twin-fluid S type, the twin-fluid MMA100 type and the single-fluid swirl type. The maximum means that the splay was conducted under the fully opened control valve in the water line. The abscissa is the power required to operate the atomizer, the pneumatic power, L_G, for the two-kinds of twin-fluid types and the hydraulic power, L_L, for the single-fluid type. In the two twin-fluid types, Q_L increases with L_G because Q_L increases with the air supply rate, Q_G. In the single-fluid type, Q_L increases with the inlet water pressure, P_{L1}, and P_{L1} is proportional to Q_L^2 because it is identical to the pressure loss through the atomizer. Since L_L is given as $Q_L \cdot P_{L1}$, Q_L becomes proportional to $L_L^{1/3}$. If ten atomizers of the single-fluid type are used at the same time, Q_L exceeds that for the twin-fluid S type, but the total of L_L is one-hundredth lower than that for the twin-fluid S type. Thus, the single-fluid type has a merit in saving energy, but has a demerit of large liquid droplet as described in Figure 13.

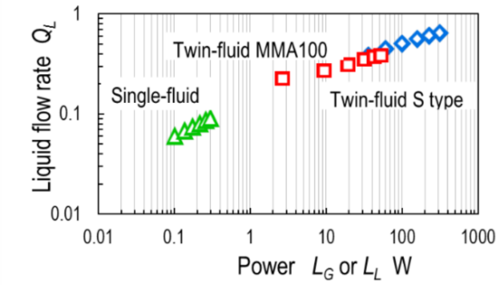


Figure 12 Comparison of the maximum mist flowrate among the twin-fluid S and MMA100 types and the single-fluid type

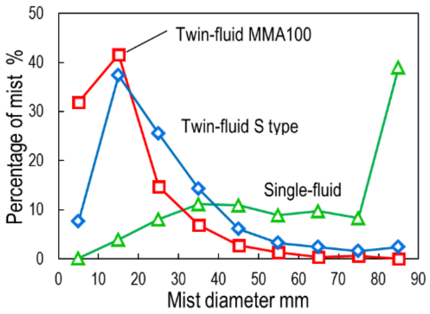


Figure 13 Comparison of droplet size distribution among the twin-fluid S and MMA100 types and the single-fluid type

Figure 13 compares droplet size distribution among the three atomizers, and Table 2 lists the operation conditions and mean and Sauter mean diameters of atomized droplets. The operation condition for the single-fluid type correspond to that shown in the maker's manual and that for the MMA100 type to the maximum Q_L, and that the S type to nearly the same Q_L as that in the single-fluid type. In the MMA100 type, 75% droplets are smaller than 20 μm, called "dry mist" and reported to be effective to the mitigation of heat island phenomena in megalopolis [11]. In the single-fluid type, 40 % droplets are larger than 80 μm, which cannot suspend in air. In the twin-fluid S type, smaller droplets than 20 μm are 45%, and 20 to 40 μm droplets are 40%, while 20% for the MMA100 type. Since the fall velocity of droplet increases with its size, the smaller and the denser droplets seem effective to adsorb harmful gases. However too small droplets like dry mist cannot adsorb them because they disappear due to evaporation.

Table 2 Operation conditions and drop sizes for three atomizers

Atomizers	Q_L l/min	Q_G l/min	d_m μm	d_{32} μm
Single-fluid swirl type	0.09	0	77	132
Twin-fluid MMA100	0.38	27	17	35
Twin-fluid S type	0.10	170	27	86

CO_2 Adsorption Performance with Mist

Figures 14(a) and (b) show the pictures of mist room just after the stop of spay in the CO_2 adsorption performance test respectively for the single-fluid swirl type and the twin-fluid S type. Q_L for the twin-fluid S type was 0.10 l/min, while that for the single-fluid swirl type was 0.09 l/min, being the same as those in the test of Figure 13. The picture for the single-fluid type is clearer than that for the twin-fluid S type because larger droplets than 80 μm in the single-fluid type cannot suspend in air because of shorter residence time by the higher fall velocity. In the twin-fluid type, however, droplets smaller than 40 μm are about 85%, and can float for a while if they were not evaporated, so the room becomes foggy as seen in Figure 14 (b).

(a) Single-fluid swirl type (b) Twin-fluid S type

Figure 14 Pictures of mist room just after the stop of spay by the single-fluid type and the twin-fluid S type

Figure 15 shows time variations in the CO_2 concentration in air at the bottom of the mist room for the following four cases: the mists filled case with the single-fluid swirl type, those with the twin-fluid MMA100 type, those with the twin-fluid S type, and no mist spray case. Shortly after the introduction of CO_2 into the mist room, CO_2 concentration detection was started at the bottom of the mist room. The CO_2 concentration in air at 25 s from the start is the same as that outside of the room, i.e., less than 500 ppm, because CO_2 could not reach to the detectors. The concentration after 25 s rapidly increased with time, and took a maximum value at 150 s or after. In no mist spray case, the concentration after the peak decreased gradually because of some leakage of CO_2 to the outside.

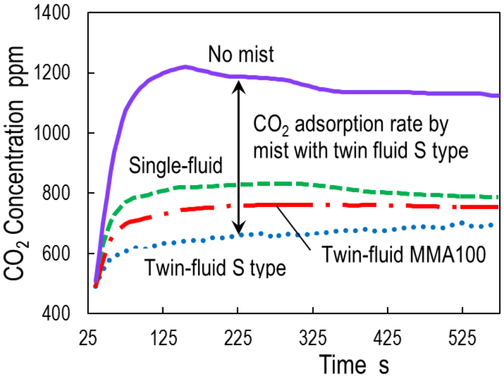


Figure 15 Time variation in CO_2 concentration in air at the bottom of mist room –Effects of mist and its generation method

The mass of CO_2 adsorbed by the mists is known from the concentration difference between the mists filled case and the no mist spray case. The CO_2 concentration difference from the no mist spray case for the twin-fluid S type is about 25% larger than that for the twin-fluid MMA100 type, and 50 % larger than that for the single-fluid swirl type. This means that the droplets around 20 to 40 μm in diameter are very effective to adsorb CO_2. From the CO_2 concentration difference between 470 ppm at 25 s and the values at 525 s, we can confirm that about 70 % of CO_2 in the mist room was adsorbed by the mists in the twin-fluid S type case while about 55 % in the twin-fluid MMA type. Thus, the twin-fluid S type is superior to the commercial two atomizers in the CO_2 adsorption by the mists under the above operation conditions.

CONCLUSIONS

Firstly, a twin-fluid water suction type atomizer invented by Sadatomi and Kawahara [2] was introduced together with its spray rate prediction method [4] and its industrial applications. Secondly, the performance of the twin-fluid atomizer with best performance [4-7], i.e., S type, was compared with those of the commercial twin-fluid MMA100 type together with the single-fluid swirl type. From the comparison among the three atomizers, the followings were clarified:

1. The ratio of the spray rate to the power required, Q_L/L_L or Q_L/L_G, was much higher in the single-fluid swirl type than the two-kinds of twin-fluid types. Thus, the single-fluid swirl type is superior in energy saving point of view.
2. The droplet size for the single-fluid swirl type was larger than those for the two twin-fluid types, and 40% droplets were larger than 80 μm, which cannot suspend in air. In the twin-fluid MMA100 type, fine droplets smaller than 20 μm was 75 % but most of them disappear due to evaporation. In the twin-fluid S type, 20 to 40 μm droplets are 40% and they can suspend in air, thus effective to adsorb harmful gases such as CO_2.
3. The CO_2 adsorption by mists was 70% in the twin-fluid S type while 55% in the twin-fluid MMA100 type. Thus, the twin-fluid S type is the best in CO_2 adsorption point of view.

ACKNOWLEDMENTS

The authors appreciate Dr. Yao J., Messrs. Sakurai E., Furusawa S., Tanaka K. and Kawano Y. very much for their cooperation in this series of studies, and financial supports from JSPS KAKENHI (Grant Number 26420117), Big Bio Co. and Kumamoto IDM Co.

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