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1 Numerical study on spout elevation of a gas-particle spout fluidized
2 bed in microwave-vacuum dryer

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16
17 **Abstract:**

18 The dynamic characteristics of gas-particle spout fluidized bed in a pulsed spouted
19 microwave-vacuum drying system (PSMVD) were investigated. The spout fluidization
20 process in a pseudo-2-D spout fluidized bed was simulated by computational fluid dynamics
21 (CFD) using the inviscid two-fluid theory method (TFM) based on the kinetic theory of
22 granular flow. The dynamic characteristics of the spout fluidized bed and the effect of spout

23 elevation on the particle movement were revealed, which could be used to improve the
 24 uniformity of particle mixing and microwave heating. The mathematical model demonstrated
 25 that the spout fluidization process includes isolated, merged and transitional jets and the
 26 fluidization at a specific spout gas velocity has a start-up stage and a quasi-steady fluidization
 27 stage. The spout velocity was an important factor controlling particle status in the spout
 28 fluidized bed and a critical velocity was identified for effect transition of the flow pattern.
 29 There was an approximately linear correlation between the jet penetration depth and the spout
 30 velocity. When the spout gas velocity increased up to the critical velocity region, the pressure
 31 drop tended to convert from negative pressure to positive pressure.

32 **Keywords:** Microwave-vacuum dryer; Spout fluidized bed; Fluid dynamics; CFD model

33

Nomenclature		Δt	time step (s)
C_D	drag force coefficient	\vec{u}	velocity vector (m/s)
d_p	particle diameter (m)	u_{spout}	spout velocity (m/s)
\vec{F}	net force (N/m ³)	Greek symbols	
g	acceleration due to gravity (m/s ²)	ε	volume fraction
H	bed height (m)	ρ	density (kg/m ³)
L	nozzle width (m)	μ	viscosity (Ns/m ²)
P	pressure (N/m ²)	Subscripts	
ΔP	bed pressure drop (N/m ²)	g	gas
Re	Reynolds number	p	particle
t	time (s)		

34

35

36 **1. Introduction**

37 In recent years, microwave-vacuum drying (MVD) has been tentatively applied in food
38 industry as a potential drying method for obtaining high quality food products, including dried
39 fruits, vegetables and grains (Zhang et al. 2010, Li et al. 2011). MVD possesses the
40 advantages of both microwave heating and vacuum drying. The combination of low
41 temperature and fast mass transfer conferred by vacuum drying and rapid energy transfer by
42 microwave heating generates a very rapid, low temperature drying process and has the
43 potential to improve energy efficiency and product quality. Although MVD can offer unique
44 advantages, the inherent problem preventing its widespread application is the nonuniform
45 temperature distribution caused by uneven spatial distribution of the electromagnetic field
46 inside the drying cavity, which results in hot and cold spots in the dried product (Li et al,
47 2011). The nonuniform temperature distribution in microwave drying also causes an issue of
48 microbial safety in food products (Vadivambal et al. 2010, Jangam et al. 2011).

49 The heating uniformity of MVD is influenced by many factors, such as vacuum cavity
50 effects, product physical attributes and geometry, spatial location, and spatial electromagnetic
51 field intensity in the microwave cavity (Zhang et al. 2006, 2010). Many researchers have
52 studied the MVD characteristics of food materials, both experimentally (Hu et al. 2006,
53 Huang et al. 2011, Nahimana et al. 2011) and theoretically using analytical and mathematical
54 methods (Giri et al. 2007, Han et al. 2010, de Jesus et al. 2011). Various field-averaging
55 methods have been developed to achieve the heating uniformity. The MW energy averaging
56 can be accomplished by either mechanical means (Torringa et al. 1996) or through pneumatic
57 agitation (Feng et al. 1998; Balakrishnan et al. 2011).

58 Fluidization provides a pneumatic agitation for particles in the drying bed. It also facilitates
59 heat and mass transfers due to a constantly renewed boundary layer on the particle surface
60 (Feng et al. 2001, Jambhale et al. 2008). Therefore, combination of fluidized or spouted bed
61 drying with MVD is considered as an effective means of solving the uneven heating problem.
62 It is well known that coarse food particles such as diced or sliced materials are difficult to be
63 fluidized by a conventional fluid bed, especially when their moisture content is relatively high
64 and surface is sticky. However, pulsed spouted bed can be used for fluidizing the coarse
65 particles. Although a few researchers have performed some experimental investigations on the
66 drying characteristics of food materials by this new technique (Wang et al. 2012, 2013), more
67 work about fluidization need to conducted to understand the drying mechanism in pulsed
68 spouted microwave-vacuum drying (PSMVD).

69 Computational fluid dynamic (CFD) approach has been recognized as a useful tool to
70 obtain detailed hydrodynamics of a complex gas-solid flow (Rahimi et al. 2013). Two
71 different methods are generally used for modeling dispersed phase flows in fluidized and
72 spouted bed, namely, Eulerian-Eulerian (EE) and Eulerian-Lagrangian (EL) methods (Pai and
73 Subramaniam 2009). In EL or discrete element method (DEM), the continuous phase flow is
74 evaluated by Eulerian approach, while the individual particle trajectories are evaluated by
75 Lagrangian approach. Although the EL approach requires less modeling assumption for the
76 particulate phase, it requires highly efficient computation to analyze dense gas-solid fluidized
77 beds (Pritchett et al. 1978, Bouillard et al. 1989). Two-fluid model (TFM) based on the EE
78 method is a popular approach requiring smaller CPU and memory resources, and has been
79 used in a large number of studies (Gidaspow et al. 1994, 2004). In the TFM model, the two

80 phases are treated as interpenetrating continua. This approach has been successfully utilized
81 for predicting and validating hydrodynamics of the gas-solid systems. For example,
82 Passalacqua and Marmo (2009) used the TFM to predict bubble diameter in a bubbling fluid
83 bed with a central jet and the bubble diameter distribution in a uniformly fed bubbling
84 fluidized bed. Zhong et al. (2010), Wang et al. (2007) and Pei et al. (2009) have also applied
85 the TFM in studying hydrodynamics of spout-fluid bed, fluidized bed coal gasification,
86 circulating fluidized beds and jet fluidized beds, respectively. The success of a TFM depends
87 on the proper description of the interfacial forces and the constitutive models for solid and
88 fluid stresses. The interfacial forces are used to describe the momentum transfer between the
89 phases, which significantly affects the hydrodynamic behavior of the two-phase flows.

90 In the present study, the effect of combining a pseudo two-dimensional spout fluidized bed
91 in a pulsed spouted microwave-vacuum drying system (PSMVD) was investigated using the
92 TFM method. The dynamic characteristics of the gas-particle spout fluidized bed and the
93 effect of spout elevation on particle movement at different spout gas velocity conditions were
94 revealed, which could be used to improve the uniformity of particle mixing and heating in a
95 PSMVD system.

96

97 **2. PSMVD equipment and materials**

98 **2.1. PSMVD equipment**

99 An experimental equipment was designed in our laboratory for the PSMVD study, which
100 consisted of the following seven basic components. The schematic diagram of the PSMVD
101 system was shown in Figure 1.

102 (1) a cylindrical multimode microwave cavity (Figure.1-3), equipped with four microwave
103 generators (at 2,450 MHz);

104 (2) a circular duct vacuum drying chamber (Figure.1-6);

105 (3) a pulse-spouted system (Figure.1-11,12,13,14), equipped with a set of adjustable gas
106 flow and distributive unit as well as a set of air handing units of 1m³/min capacity;

107 (4) a heat supply system (Figure.1-4). Each magnetron's power output was in the range of
108 0.1 to 1.0kW by a GPA-1800W microwave power controller;

109 (5) a water load system (Figure.1-5), which was added to prevent the magnetron from
110 overheating;

111 (6) a vacuum system (Figure.1-7,8,9,10) equipped with a cooler and a water-ring vacuum
112 pump with a pumping rate of 1m³/min.

113 The pressure inside the drying chamber could be regulated in the range of 3.5 to 100 kPa.

114 <Figure 1>

115 **2.2. Materials**

116 Fresh stem lettuce (*Lactuca sativa*) obtained from Haitong Food Group farm in Ningbo
117 city, China, was used as a model drying material. In this study, the lettuce particle is
118 simplified as spherical particle with a diameter of 5 mm. The physical properties of lettuce
119 dices were measured and the details were shown in Table 1, which represented a typical food
120 particle for drying (Wang et al. 2012).

121 **3. Computational models and method**

122 **3.1. The hydrodynamic model**

123 In the present study, the inviscid two-fluid theory (Gidaspow 1994; 2004) was used to

124 investigate both the fluid and particle movements in a gas-solid spout fluidized bed under
 125 vacuum pressure conditions. The continuity and momentum equations of describing gas and
 126 particle flows are given below:

127 Continuity equations:

128 Particle phase
$$\frac{\partial \varepsilon_p}{\partial t} + \nabla \cdot (\varepsilon_p \vec{u}_p) = 0 \quad (1)$$

129 Gas phase
$$\frac{\partial \varepsilon_g}{\partial t} + \nabla \cdot (\varepsilon_g \vec{u}_g) = 0 \quad (2)$$

130 Momentum equations:

131 Particle phase
$$\frac{\partial (\varepsilon_p \rho_p \vec{u}_p)}{\partial t} + \nabla \cdot (\varepsilon_p \rho_p \vec{u}_p \vec{u}_p) = \vec{F}_{p,net} \quad (3)$$

132

133 Gas phase
$$\frac{\partial (\varepsilon_g \rho_g \vec{u}_g)}{\partial t} + \nabla \cdot (\varepsilon_g \rho_g \vec{u}_g \vec{u}_g) = \vec{F}_{g,net} \quad (4)$$

134 Where ε represents the volume fraction ($\varepsilon_p + \varepsilon_g = 1$), u is the flow velocity, and \vec{F} is the
 135 net force. The subscripts g and p indicate gas and particle phase, respectively.

136 Particle-phase force component:

137
$$\vec{F}_{p,net} = -\varepsilon_p \nabla p + \nabla \cdot \overline{\overline{\tau}}_p + \varepsilon_p \rho_p \vec{g} + \sum_{p=1}^n K_{pg} (\vec{u}_p - \vec{u}_g) + \vec{F}_p \quad (5)$$

138 Gas-phase force component:

139
$$\vec{F}_{g,net} = -\varepsilon_g \nabla p + \nabla \cdot \overline{\overline{\tau}}_g + \varepsilon_g \rho_g \vec{g} + \sum_{g=1}^n K_{gp} (\vec{u}_g - \vec{u}_p) + \vec{F}_g \quad (6)$$

140 Where p is the pressure shared by all phases, $\overline{\overline{\tau}}$ is the phase stress-strain tensor, and K is
 141 the momentum exchange coefficient.

142 Gas-particle momentum exchange is calculated based on the Syamlal-O'Brien model

143 (Syamlal and O'Brien, 1989):

$$144 \quad K_{pg} = K_{gp} = \frac{\varepsilon_p \rho_p f}{\tau_p}, f = \frac{C_D \text{Re}_p \varepsilon_g}{24u_{r,p}^2} \quad (7)$$

145 Where $u_{r,p}$ is the terminal velocity correlation for the solid phase (Garside and Al-Dibouni,
146 1977):

$$147 \quad u_{r,p} = 0.5(A - 0.06 \text{Re}_p + \sqrt{(0.06 \text{Re}_p)^2 + 0.12 \text{Re}_p (2B - A) + A^2}),$$
$$148 \quad A = \varepsilon_g^{4.14}, B = \varepsilon_g^{2.65} \quad (\varepsilon_g \geq 0.85) \quad (8)$$

149 The empirical Dallavalle relation is used to express drag coefficient C_D :

$$150 \quad C_D = \left(0.63 \frac{4.8}{\sqrt{\text{Re}_p u_{r,p}}} \right)^2, \quad (9)$$

151 Where Re_p is particle Reynolds number, defined as

$$152 \quad \text{Re}_p = \frac{\rho_g |\vec{u}_p - \vec{u}_g| d_p}{\mu_g} \quad (10)$$

153 Where d_p is particle diameter, and μ_g is gas viscosity.

154 3.2. Numerical method

155 Knudsen is a dimensionless parameter of rarefied gas. Because the Knudsen of the vacuum
156 flow (absolute pressure, 7000Pa) in the present PSMVD equipment was far lower than 1, the
157 flow was consistent with fluid continuum hypothesis and solved by the Navier-Stokes equation
158 (Shen, 2005). Simulations of a gas-solid flow in PSMVD equipment were carried out on a
159 CFD package (ANSYS FLUENT, USA). Two-fluid model of Eulerian-Eulerian was used to
160 capture gas-solid flow hydrodynamic.

161 In the present pseudo two-dimensional [spout fluidized bed](#) (pseudo-2D [spout fluidized](#)
162 [bed](#)), the spouted flow was simplified to a two dimensional flow as shown in Figure 2. The

163 width of the drying chamber was 40 mm and cavity height H 516 mm; the width of air
164 distribution nozzle L was 8 mm and air distributor angle was 45 °. Air and lettuce particle
165 were used as gas and particle phase, respectively (Table 1).

166 The two dimension flow field was computed with the software of ANSYS FLUENT by
167 solving the Reynolds-Averaged Navier-Stokes equations. An implicit scheme of volume
168 fraction, a laminar viscous model, a phase coupled simple scheme, a least squares cell based
169 first order upwind spatial discretization, and a first order implicit transient formulation were
170 employed. The spouted air and lettuce particulates were set as primary phase and secondary
171 phase, respectively. The interactions between air and particulates were considered as drag and
172 collisions of granular flow.

173 A structure mesh was generated by using a grid generation ANSYS ICEM. In the flow
174 passage, the mesh contained 370,000 cells. The minimum size of cell was 0.01 mm.
175 Comparisons of the coarser mesh model (70,000 cells), the mid-mesh model (370,000 cells)
176 and the refined mesh model (750,000 cells) were carried out to ensure that the computational
177 results were independent of mesh size. The failure of the coarser-mesh may be caused by bad
178 transition elements.

179 <Figure.2>

180 Boundary conditions were defined as follows. The inlet was specified as velocity inlet,
181 and the primary phase velocity is specified. The inlet spouting gas is specified as an ideal gas
182 under the atmosphere pressure, whose properties were calculated by ideal gas state equation.
183 The outlet was specified as vacuum pressure outlet. The gravity and volume fraction of
184 particles were specified. The detailed numerical parameters of granular flow of lettuce

185 particles are listed in Table 1. The instantaneous time step was set 0.001 s. Numerical
186 simulations were carried out at the different spout gas velocities ($u_{\text{spout}} = 3.5$ m/s, 7 m/s, 14 m/s,
187 28 m/s, and 56 m/s respectively).

188 < Table 1 >

189 **4. Results and discussion**

190 To investigate the elevation characteristics of the spout fluidized lettuce particles, the
191 hydrodynamics of the gas-solid spout fluidized bed with an increasing uniform inlet gas
192 velocity were simulated.

193 **4.1. Validation of the model**

194 In order to validate this model to obtain the minimum fluidization in the spout fluidized bed,
195 the minimum fluidization velocity was identified with the spout velocity of 3.5 m/s. The solid
196 volume fraction, the phase 2 velocity and pressure at the minimum fluidization velocity were
197 shown in Figure 3, Figure 4 and Figure 5. The lettuce particles kept the traditional fixed-bed
198 state after running for 1s when the inlet gas velocity was equal to or smaller than the
199 minimum fluidization velocity.

200 It was observed that the whole fluidization process in a spout fluidized bed included an
201 initial stage and a steady stage (Figure 3, Figure 4 and Figure 5). The initial stage was an
202 instantaneous developing process where the jet flow penetrated the bed, in which the jet
203 appeared originally and then broke up periodically into bubbles without interference. The
204 second stage was a steady circulation process where the particles circulated in a fixed pattern.
205 A suspending surface of particles was formed at a height of 0.029 m from the inlet at spout
206 velocity $u_{\text{spout}} = 3.5$ m/s. Most particles occupied the bottom and few particles were able to

207 escape from this surface; the maximum particle velocity was up to 0.1 m/s.

208 <Figure.3>

209 <Figure.4>

210 <Figure.5>

211 **4.2 Flow pattern**

212 With the inlet spout gas velocity increase, the hydrodynamics of the gas-solid spout
213 fluidized bed began to change. The flow pattern in a long vacuum cavity could be considered
214 as a single jet, flow transition, and flow coalescence based on the frame-by-frame analysis
215 (Guo et al. 2001 and Hong et al. 2003), which was simplified as a pseudo-2D cavity in this
216 study. The detailed description of the flow pattern in wider operation conditions was
217 presented below. The single jet characteristic was observed at a very low fluidized velocity,
218 such as spout gas velocity 3.5 m/s as shown in Figure 3, Figure 4 and Figure 5.

219 **4.2.1 Flow stability**

220 [Figure 6](#) shows the static pressure at the middle point located at the initial particle surface at
221 different spout gas velocity. There was a clear unsteady initial process for about 1s, and after
222 this fluctuating stage it tended to become steady when the gas spout velocity was lower than
223 21m/s. The duration of the unsteady status increased with the increase of spout velocity, and
224 the pressure value tended to decrease and fluctuated as gas spout velocity increased. The
225 particle velocity at the same point is shown in [Figure 7](#). The particle velocity varied sharply at
226 the initial stage, and became steady when spout velocity was lower than 21 m/s. When spout
227 velocity was up to 28 m/s, particle velocity increased and was characterized by periodical
228 fluctuation, and the fluidization presented an oscillatory nature. The above findings indicated

229 that the spout velocity was an important factor in a spout fluidized bed. The whole process
230 could be divided into two stages: a start-up stage and a quasi-steady fluidization stage.

231 <Figure.6>

232 <Figure.7>

233 **4.2.2. Particle flow developing process**

234 Considering the fluctuation characteristics of particle flow when spout velocity was up to
235 28 m/s, the particle flow patterns at spout velocity $u_{\text{spout}} = 14$ m/s and 28 m/s were discussed
236 respectively to verify a key spout velocity affecting transition of the flow pattern, i.e. critical
237 velocity. The effect of geometry structure of 2D spout fluidized bed on particle flow pattern
238 was also evaluated.

239 [Figures 8 and 9](#) show the instantaneous particle flow pattern during spout time of 3.0 s at
240 spout velocity of $u_{\text{spout}} = 14$ m/s. The instantaneous particle flow patterns at the initial time of
241 1.0 s were obtained. It was noted that compared with spout velocity 3.5 m/s, the jet appeared
242 and developed with more and stronger bubbles, causing more motion of the particles in the
243 annulus region. Although most particles were elevated by spout gas flow, a small portion of
244 particles was found near the wall of the air distributor. The occupancy of particles occurred
245 near the bottom of the air distributor, and formed a spherical region. During the spout time
246 from 1.0 s to 3.0 s with a 0.5 s interval, the distribution of particle velocity and maximum
247 suspending height were shown in [Figure 9](#). When the particle flow pattern was in a steady
248 status, a suspending surface of particles was formed at a height of 0.045 m above the nozzle.
249 Most high particle velocities were located at the upper region of air distributor with a
250 spherical feature, which indicated that there were two particle circulation tracks in the spout

251 fluidized bed. Few particles escape from the suspending surface and the maximum value of
252 particle velocity was up to 0.26 m/s in the present study.

253 <Figure.8>

254 < Figure.9>

255 < Figure.10>

256 < Figure.11>

257 The instantaneous particle flow pattern at spout velocity $u_{\text{spout}} = 28$ m/s was obtained as
258 shown in [Figures 10 and 11](#). The instantaneous flow patterns at the initial time of 1.0s
259 indicated that the jet rapidly appeared with more and stronger bubbles, penetrated the particle
260 bed, and developed with significant elevation of most particles. The particles that
261 accumulated on the wall of the air distributor were carried to the upper region as spout jet
262 flow developed. Under this condition, the spout jet flow caused the motion of most particles
263 in the annulus and axial regions. When spout velocity was up to 28 m/s, the particle flow
264 pattern fluctuated and suspending height of particles was formed in a height range from 0.15
265 m to 0.25 m above the nozzle where the particle flow tended to be unsteady ([Figure 11](#)).
266 Compared with particle flow at spout velocity of $u_{\text{spout}} = 14$ m/s, the maximum value of
267 particle velocity was up to 1.63 m/s, and location of the higher velocity particles moved to the
268 upper region at a height range from 0.02 m to 0.1 m. There was a narrow region with low
269 particle velocity, which might have been caused by main spout gas flow.

270 The characteristics of flow patterns at different spout velocities indicated that there was a
271 correlation between spout gas flow velocity and particle status. There was a critical velocity in
272 which effect transition of the flow pattern occurred as the spout velocity increased.

273 **4.3. Effect of spout velocity on particle circulation pattern**

274 The particle circulation during drying indicates the particle mixing, and affects the heat and
275 mass transfer between different particles in a spout fluidized bed in a microwave-assisted
276 vacuum drying cavity. Penetration characteristics of spout gas flow and particle movement
277 were investigated to understand the effect of spout velocity on particle circulation pattern in a
278 pseudo-2-D spout fluidized bed.

279 **4.3.1. Penetration of spout fluidization in a pseudo-2-D spout fluidized bed**

280 In a spout fluidized bed, no matter whether the gas leaves the nozzle as bubbles, pulsating
281 jet, or permanent jet, the fact is that there exists extensive gas and solid mixing in the jet
282 region (Hong et al. 2003). The jet penetration depth is a key parameter to characterize the
283 spout gas flow, which increases with increasing jet gas velocity in the spout fluidized bed. The
284 discrepancies among various models for predicating the jet penetration depth were essentially
285 due to the different definitions of jet boundary (Musmarra, 2000). In this study, jet penetration
286 depth was defined as the contour line of voidage as 0.8 (Gidaspow and Ettehadleh 1983).
287 [Figure 12](#) shows the influence of spout gas velocity on the penetration depths and pressure
288 drop in a 2D vacuum cavity. The penetration depth increased slowly below the spout gas
289 velocity of 28 m/s, and then increased rapidly until 56 m/s. There was an approximately linear
290 correlation between the jet penetration depth and gas spout velocity.

291 The bed pressure drop is another important parameter for characterizing the particle
292 circulation pattern in a vacuum fluid bed dryer, defined as pressure difference (ΔP) between
293 the inlet and outlet of solid-gas mixture in the quasi-steady stage. The bed pressure drop at
294 different spout gas velocity is present in [Figure 12](#). The results indicated that the pressure drop

295 changed from negative pressure to positive pressure, when the spout gas velocity increased
296 from 14 m/s to 21 m/s. This phenomenon suggested a significant change of particle
297 circulation pattern that the elevated force acting on particles by the spout gas flow has
298 overcome the gravity of particles, and particles begin to be elevated from the bottom of air
299 distributor to the upper region of the vacuum cavity. Therefore, the velocity range from 14
300 m/s to 28 m/s was a critical velocity region to influence the particle circulation pattern.

301 <Figure.12>

302 **4.3.2. Particles movement**

303 Because the particle movement maintained similar features when the spout fluidized
304 process enters the quasi-steady stage (spout time is generally over 1 s), the effect of spout
305 velocity on the particle movement at spout time 3.0 s was analyzed. The distribution of
306 particle volume fraction at $t = 3.0$ s is shown in [Figure 13](#). The particle volume fraction was
307 defined as the percentage of the volume the lettuce particles occupied in the drying cavity.
308 When the spout velocity was 7 m/s, most particles accumulated near the air distributor, and
309 only a small amount of particles moved up. As the spout velocity increased to 14 m/s, most
310 particles participated in an upside movement, and formed a ball like distribution, though the
311 particles were still around the air distributor. When the velocity was increased to 21 m/s and
312 28 m/s, the particles' movements expanded to a distance of about 0.2 m from the air
313 distributor and most particles were located in this region. Finally, when the velocity was 56
314 m/s, some particles moved up to the height of 0.5 m, and most of them were located 0.2 m
315 above the jet nozzle. The results indicated that, at a constant amount of particles, particle
316 distribution was controlled by the spout gas velocity. This information might be helpful to

317 improve the microwave-assisted spout fluidized bed heating to obtain a uniform particle
318 temperature.

319 < Figure.13>

320 Figure 14 shows the particle flow patterns under different spout velocities at $t = 3.0$ s and
321 the same amount of particles. The particle velocity increased from 0.1 m/s to 3 m/s with the
322 increased spout velocity. Although the velocity distribution in the upper region above the
323 particle suspending surface was observed at low spout velocity ($u_{\text{spout}} = 7$ m/s, 14 m/s), the
324 particles' movements were mainly maintained below the particle suspending surface, and few
325 particles were existed in the region above the particle suspending surface according to the
326 distribution of the particle volume fraction. With the increase in spout velocity and
327 development of a spout jet flow, particles accumulated on the wall of the air distributor were
328 carried to the upper region. When spout velocity was increased to 56 m/s, the particle
329 movement was more spacious and significantly different from that of the transitional fluidized
330 bed. Below this spout velocity, most particles moved up instantaneously, and some of them
331 moved out of the vacuum cavity, while no apparent particle suspending surface was observed.
332 Although there was a higher particle velocity in the region with a height range from bottom to
333 0.2 m, the effect of these particles was slight because there were few particles in this region
334 according to the distribution of particle volume fraction.

335 < Figure.14>

336 The results showed that the particle circulation pattern was different under different gas
337 spout velocities. In a spout fluidized bed in a microwave-assisted vacuum dryer, the particle
338 circulation pattern was one of the important factors affecting the heating uniformity. A

339 spacious particle distribution was beneficial to obtain uniform microwave energy, and
340 improve convective heat transfer under fluidization.

341 **5 Conclusions**

342 In the present study, the TFM method was verified to successfully obtain the gas-particle
343 flow in this pseudo-2-D spout fluidized bed in a vacuum drying cavity. The dynamic
344 characteristics of spout fluidized bed and the effect of spout elevation on particle movement at
345 different operating conditions were obtained based on simulation results.

346 The model simulation illustrated that the spout fluidized process included isolated, merged
347 and transitional jets when the spout gas velocity was increased. The isolated jet turned into the
348 merged jet via the transitional jet. The fluidization at a certain velocity could be divided into
349 two stages: a start-up stage and a quasi-steady fluidization stage. The spout velocity was an
350 important factor controlling particle status in the spout fluidized bed. There was a critical
351 velocity range from 14 m/s to 28 m/s where the particle flow pattern was changed from steady
352 flow to unsteady flow.

353 There was an approximately linear correlation between the jet penetration depth and gas
354 spout velocity. The pressure drop tended to convert from negative pressure to positive
355 pressure as spout velocity increased up to the critical velocity. In the quasi-steady stage,
356 particle circulation pattern significantly changed with increased spout velocity, and particles
357 began to be elevated from the bottom of air distributor to the upper region of the vacuum
358 drying cavity.

359

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365

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455

456

457 Table 1

458 Physical and numerical parameters of the particle and gas used in the experiment

Particle phase		Gas phase	
Particle	Lettuce	Fluid	Air
Diameter, d_p (mm)	0.005	Inlet gas density, ρ_g (kg/m^3)	1.205
Density, ρ_g (kg/m^3)	1387	Viscosity, μ_g (Pa/s)	18.1×10^{-6}
Volume fraction	0.003	Cavity height, H (mm)	516
Granular viscosity(Pa/s)	Syamlal-Obrien drag model	Vacuum pressure(Pa)	7000
Granular bulk viscosity(Pa/s)	Lun-et-al model	Air distributor angle, ($^\circ$)	45
Frictional Viscosity(Pa/s)	Schaeffer,Johnson-et-al model	Nozzle width, L(mm)	8
Granular Temperature(m^2/s^2)	algebraic model	Grid number	370,000
Solid pressure(Pa)	Lun-et-al model	Grid type	Structure
Radial Distribution	Lun-et-al model	Time step, Δt (s)	1×10^{-3}
Elasticity Modulus(Pa)	Lun-et-al model		
Packing limit	0.63		

459

460

461 **Figure captions**

462 Figure.1 Schematic diagram of a pulsed spouted microwave-vacuum drying system

463 Figure.2 Computational models of air distribution structure

464 Figure.3 Particle volume fraction at the minimum spout fluidization velocity ($u_{\text{spout}} =$

465 3.5m/s , $t = 0.2\text{s}-1.0\text{s}$)

466 Figure.4 Pressure at the minimum spout fluidization velocity ($u_{\text{spout}} = 3.5\text{m/s}$, $t = 0.2\text{s}-1.0\text{s}$)

467 Figure.5 Particle velocity ($u_{\text{spout}} = 3.5\text{m/s}$, $t = 1.0\text{s}-3.0\text{s}$)

468 Figure.6 Fluctuation of static pressure at different spout gas velocity

469 Figure.7 Fluctuation of particle velocity at different spout gas velocity

470 Figure.8 Particle volume fraction at the critical spout fluidization velocity at initial stage

471 ($u_{\text{spout}} = 14\text{m/s}$, $t = 0.1\text{s}-1.0\text{s}$)

472 Figure.9 Particle velocity distribution at different spout time ($u_{\text{spout}} = 14\text{m/s}$)

473 Figure.10 Particle volume fraction distribution during spout time from 0.1s-1.0s ($u_{\text{spout}} =$

474 28m/s , $t = 0.1\text{s}-1.0\text{s}$)

475 Figure.11 Particle velocity ($u_{\text{spout}} = 28\text{m/s}$) of separation surface position

476 Figure.12 Penetration depth and pressure drop for a 2D vacuum cavity

477 Figure.13 Contour plot of the particle volume fraction in pseudo-2D spout fluidized bed

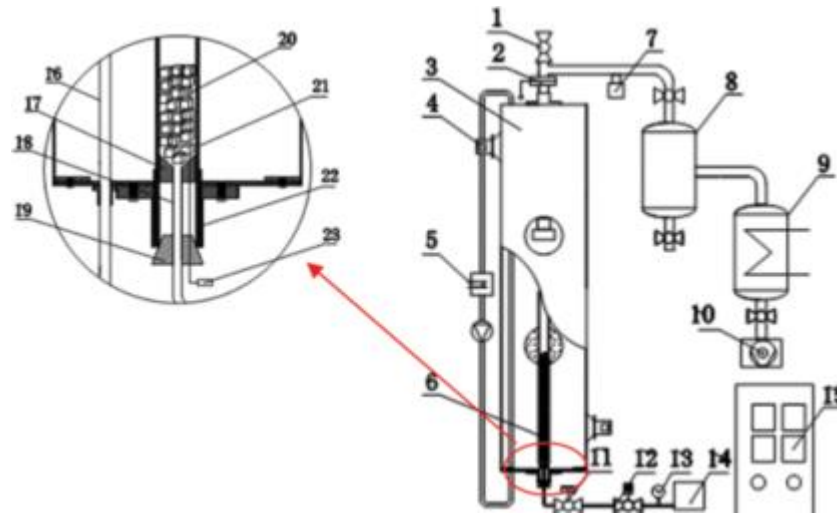
478 at different spout velocity at $t = 3.0\text{s}$

479 Figure.14 Contour plot of the particle velocity in pseudo-2D spout fluidized bed at

480 different spout velocity at steady stage ($t = 3.0\text{s}$)

481

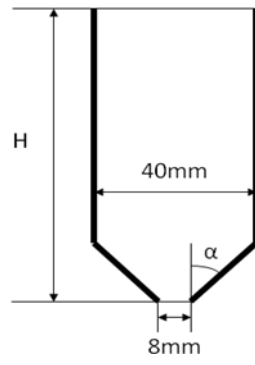
482



483
 484 Figure.1 Schematic diagram of a laboratory pulsed spouted microwave-vacuum
 485 drying system

486 1 feeding ball valve, 2 plate valve, 3 microwave heating cavity, 4 magnetron, 5
 487 circulating water unit, 6 drying chamber, 7 and 13 pressure gauge, 8 solid-gas separator,
 488 9 vapor condenser, 10 vacuum pump unit, 11 gas flow electromagnetic valve, 12 gas
 489 flow adjustable valve, 14 gas source, 15 control panel, 16 water load pipe, 17 gas
 490 distributor, 18 spout pipe, 19 silicon rubber stopper, 20 sample, 21 drying chamber, 22
 491 fixed unit, 23 fiber optic temperature sensor

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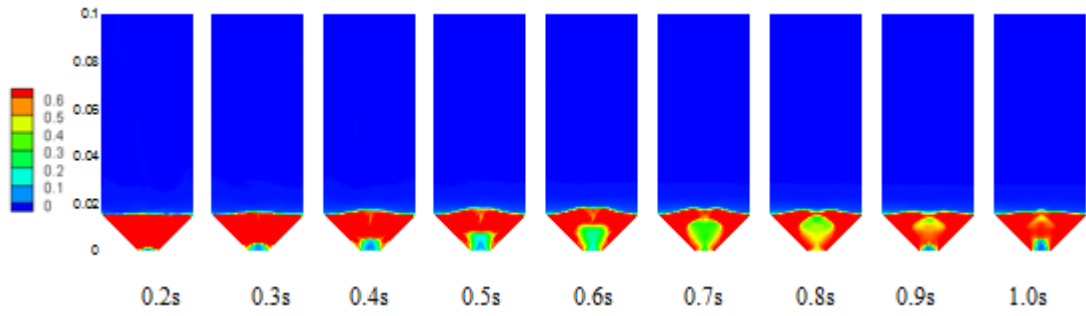


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Figure.2 Computational models of air distribution structure



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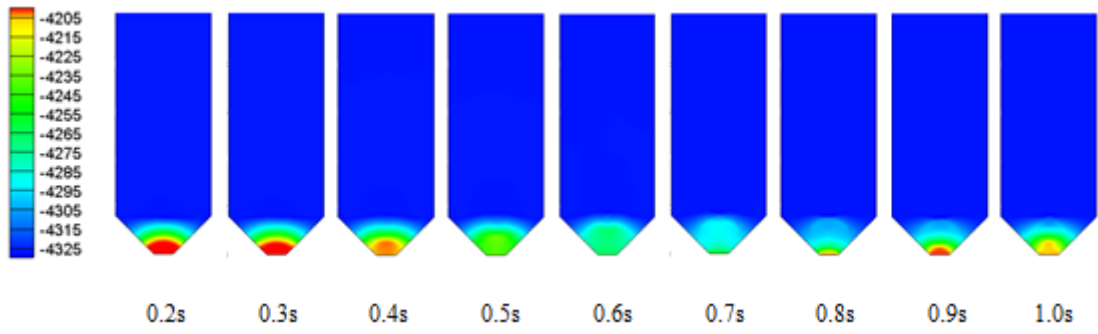
Figure.3 Particle volume fraction at the minimum spout fluidization velocity

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($u_{spout} = 3.5\text{m/s}$, $t = 0.2\text{s}-1.0\text{s}$)

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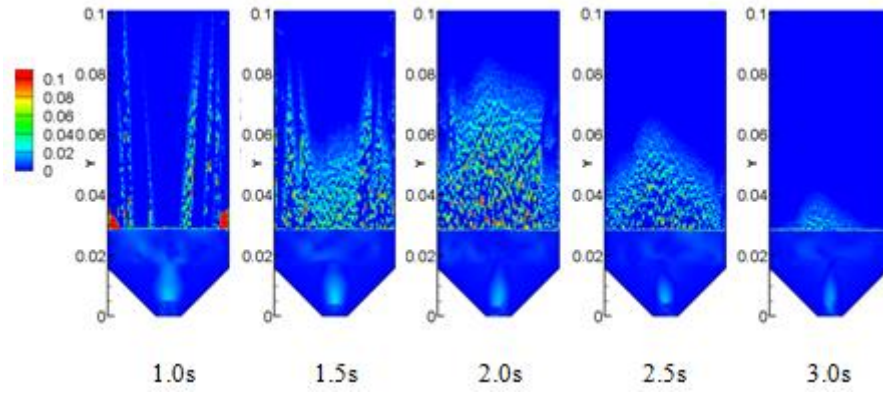
Figure.4 Pressure at the minimum spout fluidization velocity

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($u_{spout} = 3.5 \text{ m/s}$, $t = 0.2 \text{ s} - 1.0 \text{ s}$)

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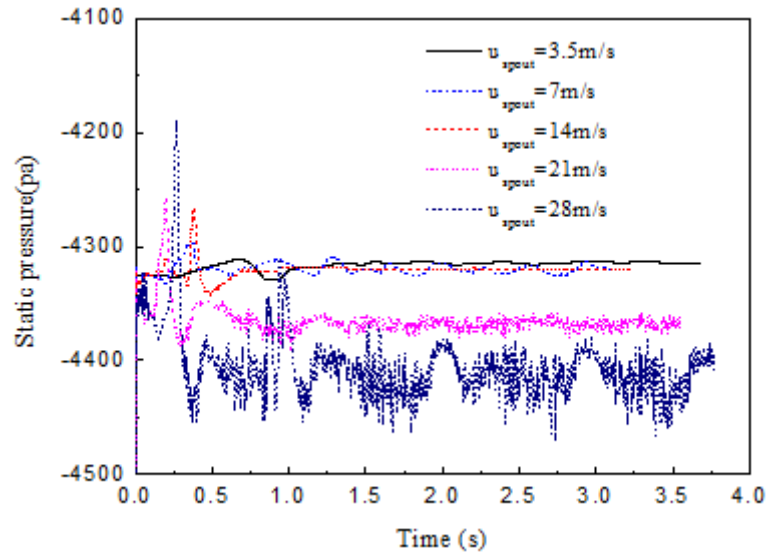


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Figure.5 Particle velocity ($u_{\text{spout}} = 3.5\text{m/s}$, $t=1.0\text{s}-3.0\text{s}$)

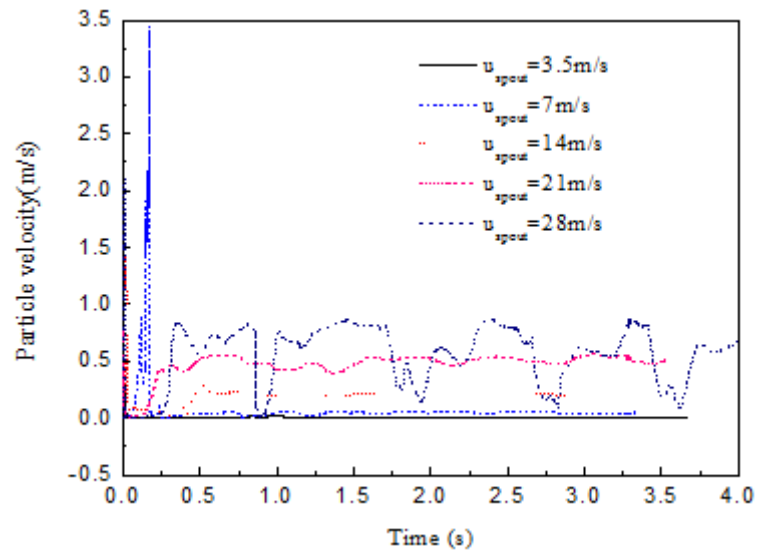


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Figure. 6 Fluctuation of static pressure at different spout gas velocity

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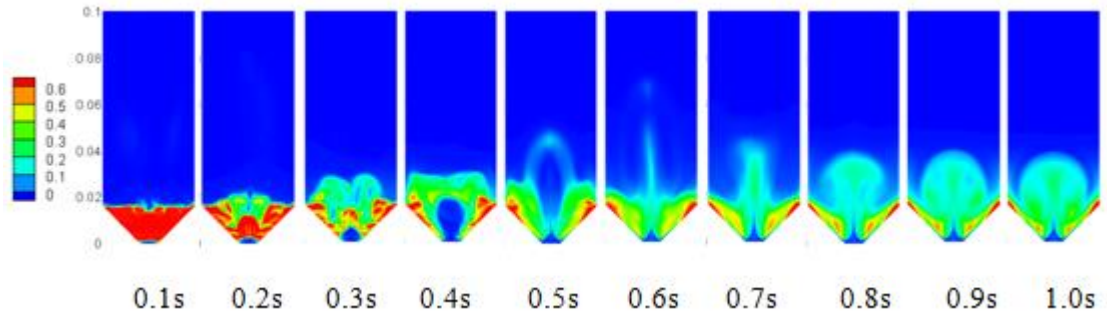


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Figure. 7 Fluctuation of particle velocity at different spout gas velocity

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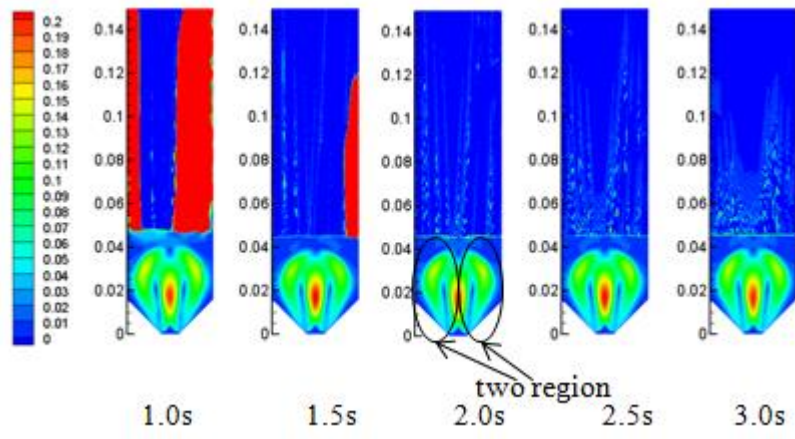
515

516 [Figure.8](#) Particle volume fraction at the critical spout fluidization velocity at initial stage

517

($u_{\text{spout}} = 14\text{m/s}$, $t = 0.1\text{s}-1.0\text{s}$)

518

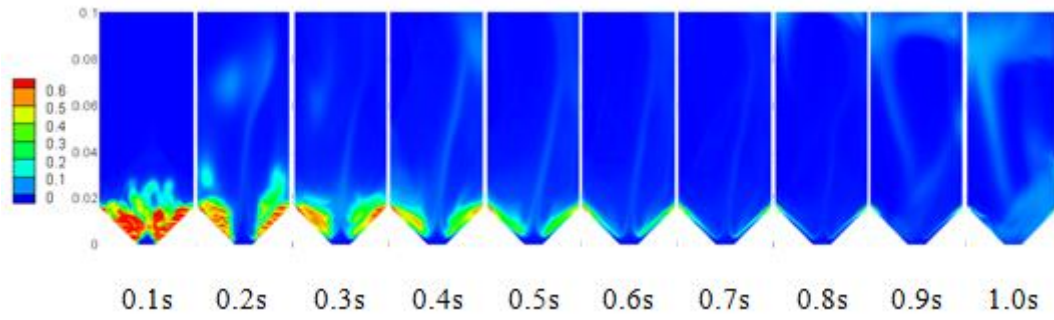


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Figure.9 Particle velocity distribution at different spout time ($u_{spout} = 14\text{m/s}$)

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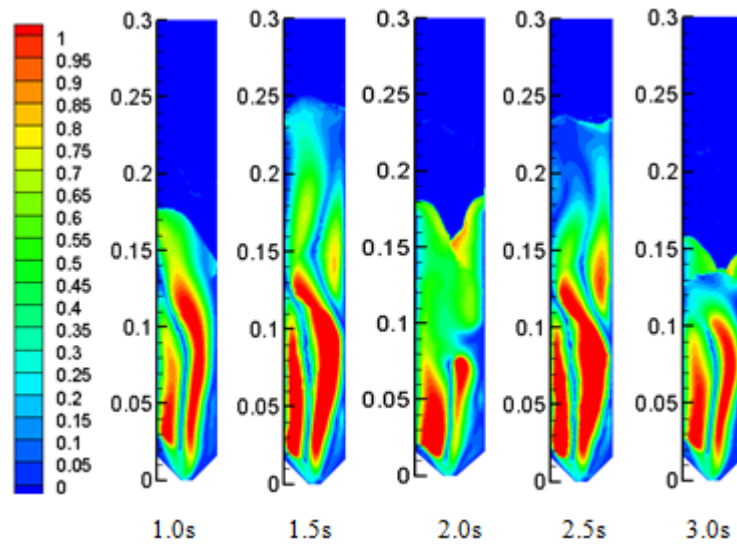
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Figure.10 Particle volume fraction distribution during spout time from 0.1s-1.0s

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($u_{\text{spout}} = 28\text{m/s}$, $t = 0.1\text{s}-1.0\text{s}$)

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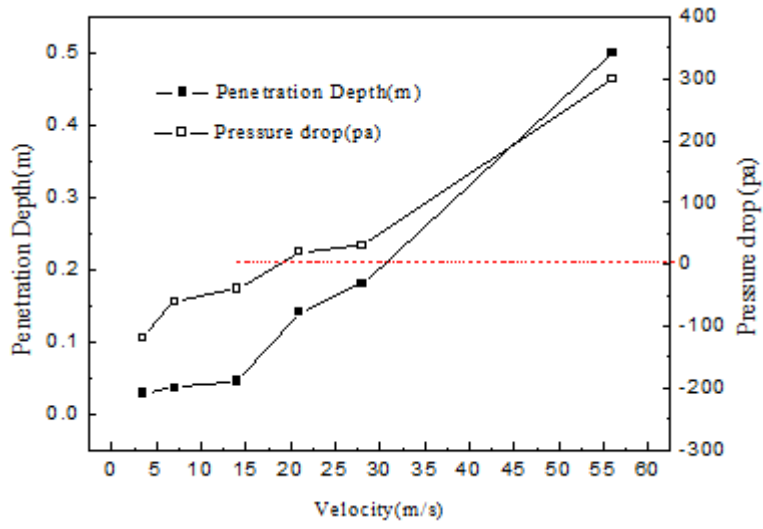


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Figure.11 Particle velocity ($u_{\text{spout}} = 28\text{m/s}$) of separation surface position

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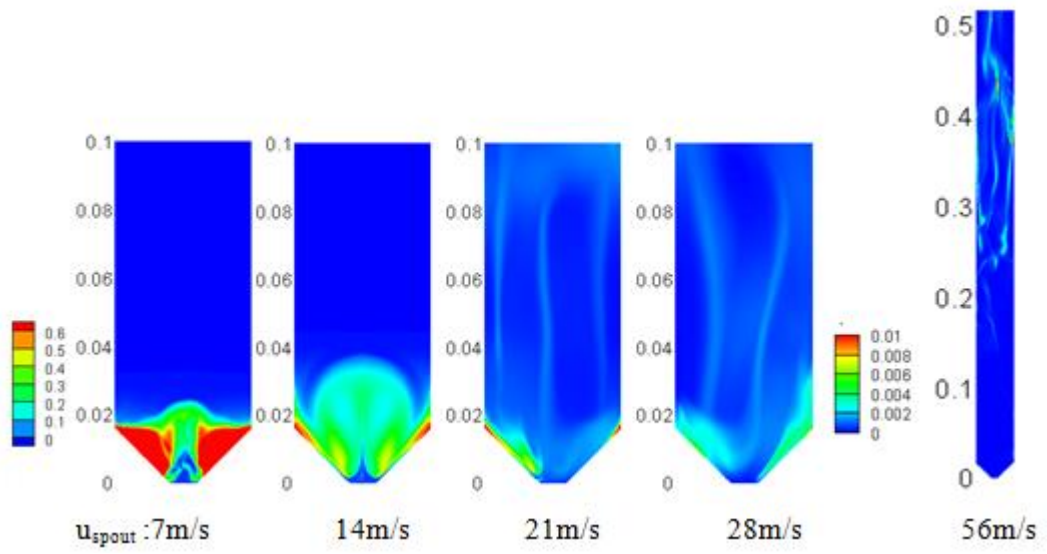


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Figure. 12 Penetration depth and Pressure drop for a 2D vacuum cavity

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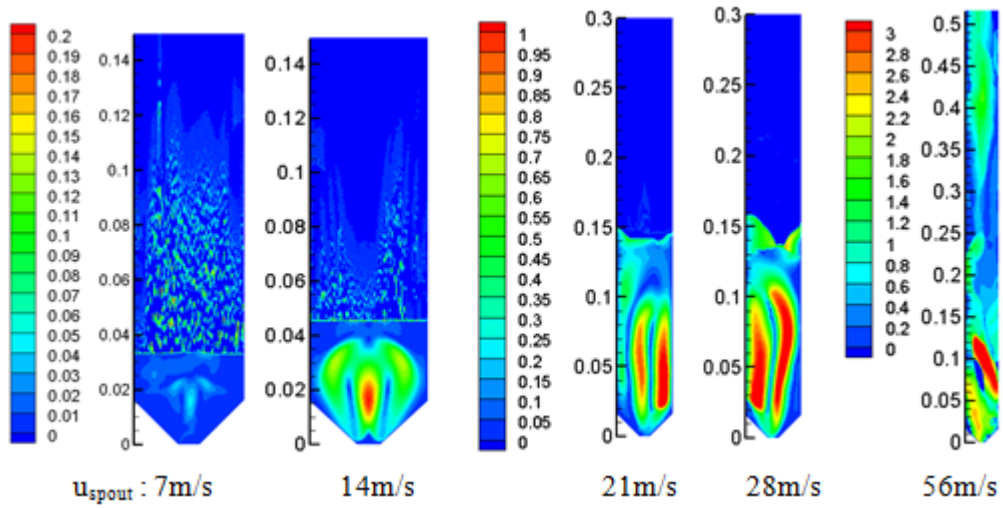
Figure.13 Contour plot of the particle volume fraction in pseudo-2D spout fluidized

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bed at different spout velocity at $t=3.0\text{s}$

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Figure. 14 Contour plot of the particle velocity in pseudo-2D spout fluidized bed at

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different spout velocity at steady stage ($t=3.0s$)

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