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4 **An experimental investigation of the explosion characteristics of**
5 **dimethyl ether-air mixtures**
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An experimental investigation of the explosion characteristics of dimethyl ether-air mixtures

Abstract

In this work, experiments are performed to study the explosion characteristics of dimethyl ether (DME) -air mixtures using a standard 20-L spherical explosion test apparatus. The experimental data reported in this paper includes: the maximum explosion pressure (p_{\max}), flammability limits, maximum rate of pressure rise $(dp/dt)_{\max}$, and combustion properties (i.e., laminar burning velocity, flame radius) of DME-air mixtures at different initial conditions. The experimental results indicate that the variation between p_{\max} and DME concentration (C_{DME}) exhibits a typical inverse “U” shaped behavior, with the peak p_{\max} at slightly larger than the stoichiometric concentration. p_{\max} is also found to decrease as the initial pressure goes down. As the initial pressure decreases from 100 kPa to 40 kPa, the lower flammability limit (LFL) is observed to vary slightly, while the upper flammability limit (UFL) is found to have a more significant drop. The relation between $(dp/dt)_{\max}$ and C_{DME} behaves similarly as that of p_{\max} as a function of C_{DME} , and the explosion pressure rises more abruptly at higher initial pressure. A satisfactory agreement is also found between the laminar burning velocity determined experimentally from the pressure measurement and that computed by PREMIX simulations. The present experimental results also show that the increase of the dimensionless radius of the flame is slower at higher initial pressure.

Keywords: Dimethyl ether; Maximum explosion pressure; Flammability limits; Maximum rate of pressure rise; Laminar burning velocity; Flame radius.

57 **1 Introduction**

58 Dimethyl ether (DME:CH₃OCH₃) is a promising oxygenated fuel that has the potential to be
59 used as an alternative to natural gas for power production and as a substitute for diesel fuel.
60 DME has high oxygen content of 35 % by weight, making the combustion smokeless and a high
61 tolerance to exhaust gas recirculation [1]. The use of DME has been proven to significant
62 decrease particulate formation, nitrogen or sulfur oxides (NO_x and SO_x), and carbon monoxide
63 (CO) emission [2, 3]. DME also has a high Cetane number of 55 to 60 and a boiling point of
64 -25 °C. These properties are ideal for fast mixture formation, reduction in ignition delay, and
65 cold start for diesel engines [4].

66 Due to its potential as a future alternative fuel, the combustion characteristics of DME have
67 attracted significant attention in recent years [5-10]. A number of experimental and numerical
68 studies can be found in the literature on the combustion and emission characteristics of DME
69 under engine conditions [11-13]. Fundamental properties such as flammability and laminar
70 burning velocities [14-17], and combustion processes of DME under turbulent conditions [3]
71 were also reported. Detailed chemical mechanisms for low and high temperature DME oxidation
72 have been developed and validated [18, 19], and a recent mechanism for DME mixture at high
73 pressures was also constructed by Burke et al. [20]. Furthermore, the effects of DME addition
74 on the high-temperature ignition and burning properties of methane-air mixtures were studied
75 experimentally and numerically [21]. Premixed and non-premixed ignition of methane/DME
76 binary fuel blends with hot air has been investigated through numerical simulation with detailed
77 chemistry and complete thermo-chemical as well as transport properties [22]. Detonation
78 velocities and characteristic cell sizes of DME-oxygen and DME-air mixtures have been
79 measured by Ng et al. [23] and Diakow et al. [24], and the explosion and detonation

80 characteristics of DME were experimentally investigated using a 180-L spherical vessel and a
81 large-scale detonation tube by Mogi and Horiguchi [25]. In addition, experiments were also
82 carried out to examine the leakage and explosion of liquid DME [26].

83 While DME flames have been studied extensively, comparatively little information exists
84 on the explosion characteristics, e.g., flammability limits, maximum explosion pressure, p_{\max} ,
85 maximum rate of pressure rise, $(dp/dt)_{\max}$ of DME at various initial conditions. The knowledge
86 of the explosion characteristics of DME is of importance to ensure the safety in industries that
87 produce or use it. A realistic assessment of the explosion hazards of DME is necessary for
88 preventive measures of explosion accidents and the design of effective mitigation schemes.
89 Among those aforementioned combustion and explosion characteristics, a key combustion
90 property is the laminar burning velocity (S_L) which is the velocity of a steady one-dimensional
91 adiabatic free flame propagating in the doubly infinite domain [27]. It received particular
92 attention not only because it represents a basic characteristic property (e.g., reactivity, diffusivity,
93 and exothermicity) of the premixed combustible gasses [28], its accurate knowledge is also
94 essential for engine design, modeling of turbulent combustion, and validation of chemical
95 kinetic mechanisms. In addition, the determination of laminar burning velocity is very important
96 for the analysis and calculations used in the field of explosion protection [29]. Besides
97 experimental measurement, the laminar burning velocity can also be estimated by numerical
98 calculation through PREMIX simulations [30], or by semi-empirical mathematical model [31,
99 32]. The results obtained from experimental measurement and numerical calculation can then be
100 compared for validation and assessment, together with data reported in the literature [4, 33].

101 The objective of the present study was twofold. First, the explosion parameters of DME-air
102 mixtures are systematically measured from experiment. The explosion parameters include: the

103 maximum explosion pressure p_{\max} , both lower flammability limit (LFL) and upper flammability
104 limit (UFL), and the maximum rate of pressure rise $(dp/dt)_{\max}$. Second, the combustion
105 characteristics (i.e., laminar burning velocity and the evolution of flame radius) are examined in
106 detail under different initial conditions. The laminar burning velocity obtained from different
107 methods are also compared and discussed.

108

109 **2 Experimental details**

110 **2.1 Experimental setup**

111 Measurements of the explosion parameters in DME-air mixtures were carried out in a standard
112 20-L explosion spherical vessel conforming to the international standard ISO6184-1, see Fig. 1.
113 It essentially consists of an explosion chamber, an electric ignition system, a control unit, a data
114 acquisition system, a release valve, a vacuum pump and an air compressor. High-voltage electric
115 spark was used to supply ignition energy as in previous studies [34-39]. The igniter was
116 mounted at the center of the spherical bomb and a spark energy of 10 J, estimated from $1/2 CU^2$
117 (“ C ” and “ U ” refer the capacitance and voltage, respectively. $C = 0.1102 \times 10^{-3}$ F, $U = 426$ V),
118 was delivered by an electric ignition system.

119

120 **2.2 Experimental procedure and conditions**

121 For the explosion experiments, gas concentrations were regulated by the gas partial pressures.
122 The purity of the DME used in this experiment is 99.8 %. During the experiments, the explosion
123 pressure evolutions were measured by a PCB pressure transducer installed in the vessel wall and
124 recorded by a data acquisition system for each shot. These data yielded values of the maximum
125 explosion pressure and maximum rate of pressure rise as illustrated in Fig. 2. This figure shows

126 a typical pressure history of the DME-air of $C_{\text{DME}} = 10\%$ at an initial pressure p_0 of 100 kPa.
127 The combustion time t_c is defined as the period from ignition to the time when the overpressure
128 reaches its maximum. The measurements were repeated at least 3 times, and results were
129 presented in the figures with error bars determined by the standard deviation. The main sources
130 of the small variation can stem from the effect of wall cooling, ignition source, the degree of
131 mixture homogeneity and asymmetry [40]. In this study, a wide range of initial conditions of
132 DME-air mixtures were used. The initial pressure ranges from 40 kPa to 100 kPa, and fuel
133 concentrations are from 3 to 19.5 %.

134 **3 Results and discussion**

135 **3.1 Maximum explosion pressure**

136 Gas explosion max-overpressure is an important parameter of evaluating the explosion hazard. It
137 reflects the energy distribution of explosive waves in their propagation process [41-46]. The
138 measurement of the explosion pressure in quiescent DME-air mixtures with various
139 compositions at the ambient condition are summarized in Table 1. In this table, p_{max} and its
140 corresponding t_c are directly obtained from the pressure history. For comparison, the adiabatic
141 pressure p_{ad} is also given and is calculated from thermo-chemical analysis using the GASEQ
142 software [47]. These experimental data of p_{max} are also compared with those reported by Mogi
143 and Horiguchi [25], and a curve fit of p_{max} using smoothing splines is also given for better
144 comparison, see Fig. 3. The explosion pressure reaches its maximum value at a composition of
145 7.5 %, which is slightly larger than the stoichiometric concentration (6.5 %). A similar behavior
146 is also observed by Mogi and Horiguchi [25] in their 180-L spherical vessel. Near the
147 stoichiometric condition, both the present data as well as the results by Mogi and Horiguchi [25]
148 agree well with the adiabatic explosion pressure determined from chemical equilibrium within

149 the experimental uncertainties. The experimental measurement starts to deviate from the
150 adiabatic pressure at off-stoichiometric conditions, prominently on the rich side. As pointed out
151 by Mogi and Horiguchi [25], at those conditions the combustion speed decreases and the event
152 departs from its constant-volume explosion character. Incomplete combustion and the effect of
153 cooling also give rise to this discrepancy, which are susceptible to the scale of the apparatus. In
154 fact, it can also be seen from Fig. 3 that, the results of p_{\max} from this study are slightly larger
155 than those of Mogi and Horiguchi near stoichiometric concentration, though within
156 experimental uncertainties. A contrary behavior is also observed as the composition tends to
157 both the fuel lean and rich sides. It is noteworthy that in [25], Mogi and Horiguchi used a 180-L
158 spherical vessel, while the present study is performed using a 20-L one. Thus, the discrepancy at
159 off-stoichiometric conditions can be caused by the wall cooling effects. Near stoichiometric
160 conditions, the combustion speed is high and the cooling rate has less influence on the
161 overpressure. However, for incomplete combustion where the temperature is lower (i.e., at off
162 stoichiometric conditions), the combustion speed becomes slower, which allows a longer time
163 scale of the phenomenon for the cooling effect to come into play. The faster cooling of a smaller
164 volume in the 20-L chamber, as compared to the 180-L large-scale apparatus used by Mogi and
165 Horiguchi [25], thus results in a lower overpressure.

166 Figures 4 to 6 show the results of p_{\max} for different DME compositions at an initial pressure
167 lower than the atmospheric condition, i.e., 80 kPa, 60 kPa and 40 kPa. To show the general trend
168 in the experimental data, curve fits using a third order polynomial are also plotted for better
169 visualization. Note that there is no previous experimental data at those pressure values for direct
170 comparison. Therefore, the measured data are merely compared with the chemical equilibrium
171 results obtained using the GASEQ software [47]. Similarly, large difference is observed as the

172 condition moves toward the LFL and UFL. Again, the theoretical maximum explosion pressure
173 determined from the equilibrium calculation is based on the hypothesis of ideal adiabatic
174 explosion. As the composition tends to fuel-lean or fuel-rich sides, not only incomplete reaction
175 occurs but also the heat loss to the surrounding can affect the explosion process, making the
176 measured values different from the chemical equilibrium calculation of an ideal adiabatic
177 explosion. It is observed from Figs. 4 to 6 that the value of p_{\max} goes down as the initial pressure
178 decreases. This observation perhaps suggests that the faster reactivity induced by the higher
179 initial pressure reduces the effect of heat losses on the explosion process. Hence, the higher
180 initial pressure may maintain higher explosion temperature, which in turn results in the rise of
181 overpressure.

182

183 **3.2 Flammability limits**

184 Table 2 shows the LFL and UFL for the DME-air mixture at different initial pressures. These
185 limits were determined when half of the shots at the same condition indicate no occurrence of
186 explosion. It is observed that the LFL has only a small fluctuation as the initial pressure
187 decreases, i.e., only a small increase from 3.5 % to 3.75 % as the initial pressure changes from
188 100 kPa to 40 kPa. However, the UFL is found to have relatively a more significant drop, which
189 changes from 19 % to 12.5 %. Reducing the initial pressure is found to narrow the interval width
190 of these two limits. It is worth to point out that this observed behavior is similar to hydrogen/air
191 [48] in which the lower flammability limit is not significantly sensitive to the initial pressure,
192 while the latter has more significant effect on the UFL. From the chemical kinetic point-of-view,
193 the effect of pressure increase has an influence on the reaction rates, especially those involved
194 third body collisions. As shown in [33], reaction steps involving H and methyl radicals show

195 greater sensitivity for rich mixtures at high pressure. Such kinetic effect may thus render the
196 UFL more sensitive to the initiate pressure.

197

198 **3.3 Maximum rate of pressure rise**

199 The maximum rate of pressure rise $(dp/dt)_{\max}$ is a commonly examined parameter for explosion
200 characteristics evaluation and used in deflagration index determination as in several previous
201 studies [49, 50]. The results of $(dp/dt)_{\max}$ as a function of DME concentration at different initial
202 pressures are shown in Fig. 7. It can be seen that, the relation between $(dp/dt)_{\max}$ and C_{DME} is
203 very similar as that of p_{\max} as a function of C_{DME} . The result indicates that the pressure rises
204 more abruptly at higher initial pressure. While for the same initial pressure, the value of
205 $(dp/dt)_{\max}$ is larger near the stoichiometric condition.

206 It is noteworthy that the rate of pressure rise reaches its maximum value at a slightly higher
207 concentration of approximately 7.5 % ($\varphi = 1.159$) than the stoichiometric condition ($\varphi = 1$), with
208 a mean value of 46.09 MPa/s. Although this behavior is similar to that for the natural gas
209 (NG)-air mixture observed in Zhang et al. [29] (with an average value of 18.86 MPa/s at the NG
210 concentration of 10.5 % or $\varphi = 1.117$), yet the pressure increases more abruptly in DME-air than
211 in NG-air mixtures.

212

213 **3.4 Laminar burning velocity**

214 Laminar burning velocity (S_L) is a unique property of a combustible mixture, indicating its
215 reactivity and exothermicity in a given diffusive medium. Since it contains the physico-chemical
216 information of the mixture, many premixed flame phenomena, e.g., extinction, flash back,
217 blow-off, and turbulent flame propagation, can be characterized with S_L being a reference

218 parameter [28]. In this study, the laminar burning velocity is computed through two different
 219 methods. The first one uses the PREMIX module of the CHEMKIN-II. The PREMIX code
 220 adopts a hybrid time-integration/Newton-iteration technique to solve the steady-state mass,
 221 species and energy conservation equations for a freely propagating flame. It has been widely
 222 used in many previous studies [21, 51-54]. In this study, 1200 grid points are imposed in the
 223 PREMIX calculations to assure a fully converged prediction. Also a small time-step $\Delta t =$
 224 5.0×10^{-7} sec is used for the computation. The present PREMIX calculation is coupled with the
 225 reaction scheme [14] involving 46 species and 263 reactions. This reaction mechanism was also
 226 used previously by Chen et al. [21] to perform PREMIX calculations of the laminar burning
 227 velocities for DME/CH₄/air mixtures. The mechanism was verified by Chen et al. [21] by
 228 comparing measured laminar burning velocities from experiment with calculations and the result
 229 shows reasonable agreement with the largest difference less than 10 %. The second method
 230 considers a mathematical model proposed by Dahoe et al. [31, 32], in which the laminar burning
 231 velocity depends on p_{\max} and dp/dt . S_L calculated by this model was also used in our previous
 232 study of NG-air mixtures [29]. The model gives the following expression:

$$233 \quad S_L = \frac{1}{(p_{\max} - p_0)} \frac{1}{3} \left(\frac{4\pi}{3V} \right)^{-1/3} \left(\frac{p_0}{p} \right)^{1/\gamma} \left[1 - \left(\frac{p_0}{p} \right)^{1/\gamma} \times \left(\frac{p_{\max} - p}{p_{\max} - p_0} \right) \right]^{-2/3} \frac{dp}{dt} \quad (1)$$

234 where V is the vessel volume, p and p_0 are the actual pressure and initial pressure, γ the adiabatic
 235 coefficient of the unburned gas. S_L is determined by a fitting method proposed by Dahoe, in
 236 which S_L is calculated by fitting the pressure history measurement (i.e., actual pressure p and
 237 dp/dt). A pressure (p)- laminar burning velocity (S_L) curve is then obtained. Afterwards, S_{L0} at
 238 the reference pressure (i.e., 100 kPa) can be determined by the extrapolate data from a linear
 239 curve fit of p - S_L . [55-57]. S_L is calculated at a flame radius greater than 6 mm to avoid the effect

240 associated to the spark ignition [58], so the result can be considered as an ideal spherical flame
241 propagating outward.

242 The laminar burning velocity of DME-air mixtures at different equivalence ratios under 100
243 kPa determined using the two aforementioned techniques are shown in Fig. 8. The reported
244 results by Qin and Ju [33] and Daly et al. [4] are also included in the same figure for comparison.
245 As shown in Fig. 8, it appears that the computed laminar burning velocity from Eq. (1) agrees
246 reasonably well with the PREMIX simulation. The largest difference between these two sets of
247 data is 42.93 % at the fuel rich condition at 100 kPa. At this condition however, the results from
248 Eq. (1) are very close to the experimental data reported by Qin and Ju [33]. Overall, one can
249 argue that the above comparison shows no significant difference for computing the laminar
250 burning velocity using Eq. (1) and the PREMIX code. Similar comparisons of the computed
251 laminar burning velocity of DME-air mixtures at different equivalence ratios with initial
252 pressures of 80 kPa, 60 kPa and 40 kPa are also shown in Fig. 9. Again, a reasonable agreement
253 between the two results still holds.

254 Figures 8 and 9 also indicate a decreasing trend of S_L with the increase of initial pressure,
255 e.g., S_L is found to be 61.52 cm/s at 40 kPa which is larger than 48.40 cm/s at 100 kPa at the
256 same composition of $C_{DME} = 7.5$ %. The behavior of decreasing trend of S_L with the increase of
257 initial pressure is caused by the increasing density, ρ_u , with increasing pressure. As demonstrated
258 by Law [28], the eigenvalue for flame propagation is $S_L = f^0/\rho_u$, (where f^0 and ρ_u are the mean
259 laminar burning flux and density, respectively). By increasing pressure, f^0 increases. It
260 demonstrates that the increase in density with pressure dominates over the retarding effect of S_L .

261

262 3.5 Flame radius

263 The flame radius, r_f , is also calculated through the equation proposed by Dahoe et al. [31, 32] as
264 follows:

$$265 \quad r_f = \left(\frac{3V}{4\pi} \right)^{1/3} \left[1 - \left(\frac{p_0}{p} \right)^{1/\gamma} \left(\frac{p_{\max} - p}{p_{\max} - p_0} \right) \right]^{1/3} \quad (2)$$

$$266 \quad \bar{r} = r_f / r_a \quad (3)$$

267 where r_f is the flame radius, r_a the radius of the vessel and \bar{r} the dimensionless radius of burned
268 gas. The typical results for stoichiometric DME-air mixtures at different initial pressures are
269 shown in Fig. 10. It can be seen that the flame radius increases just after the time of 0.02 sec,
270 and it increases rapidly until it reaches the wall of the spherical chamber. This process is
271 established as the pressure rise stage. Figure 10 also shows that at the same given time, the
272 dimensionless radius of the flame is relatively greater (i.e., the flame propagates to a longer
273 distance at the same time) at lower initial pressure, which is due to the higher burning velocity.

274

275 4 Concluding remarks

276 This paper presents a detailed investigation on the explosion characteristics (i.e., maximum
277 explosion pressure, flammability limits, maximum rate of pressure rise) and combustion
278 properties (i.e., laminar burning velocity, flame radius) of DME-air mixtures. Experiments are
279 performed by systematically measuring the pressure evolutions in a standard 20-L explosion
280 spherical vessel.

281 The present measurement shows that the variation between p_{\max} and DME concentration
282 (C_{DME}) exhibits a typical inverse “U” shaped behavior, and p_{\max} reaches its peak value when its
283 equivalence ratio is slightly larger than 1. It is found from the present measurement that p_{\max}

284 decreases as the initial pressure goes down. The flammability region is found to be from 3.5 %
285 to 19 % of DME by volume at the ambient condition. As the initial pressure decreases from 100
286 kPa to 40 kPa, the LFL varies slightly and shows little sensitivity to the initial pressure, while
287 the UFL exhibits a more significant drop. The experimental data also show that the explosion
288 pressure rises more abruptly at higher initial pressure. The relation between $(dp/dt)_{\max}$ and C_{DME}
289 is found to be very similar to that of p_{\max} as a function of C_{DME} . Laminar burning velocity was
290 also estimated using both the PREMIX simulation and a mathematical model based on the
291 measured pressure evolution, and a satisfactory agreement is found between those results,
292 especially for $C_{\text{DME}} \leq 9.5\%$. A decreasing trend of S_L is observed with the increase of initial
293 pressure. This is due to the resulting increase in density with pressure causing the decreasing the
294 observed retarding effect of S_L . Finally, the calculated dimensionless radius of the flame from
295 the pressure history is found to be smaller at higher initial pressure.

296

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460 **Tables**

461

462 Table. 1 Mixture compositions for the experimental tests, along with maximum explosion

463 pressure p_{\max} , corresponding combustion time t_c , and adiabatic pressure p_{ad}

464 Table. 2 Flammability limits of DME-air at different initial pressures

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Table. 1

Test n.	DME % v/v	O ₂ % v/v	N ₂ % v/v	p_{ad} MPa	p_{max} MPa	$p_{ad}-p_{max}$ MPa	t_c s
1	3.0	20.37	76.63	0.6042	0.1000	0.5042	—
2	3.5	20.27	76.24	0.6699	0.1446	0.5253	0.3574
3	4.0	20.16	75.84	0.7316	0.4687	0.2629	0.2612
4	5.0	19.95	75.05	0.8406	0.8844	-0.0438	0.1064
5	6.0	19.74	74.26	0.9244	1.0011	-0.0767	0.0726
6	6.5	19.64	73.87	0.9548	1.0578	-0.1030	0.0732
7	7.0	19.53	73.47	0.9770	1.0767	-0.0997	0.0610
8	7.5	19.43	73.08	0.9908	1.0781	-0.0873	0.0668
9	8.0	19.32	72.68	0.9971	1.0447	-0.0476	0.0610
10	9.0	19.11	71.89	0.9953	0.9953	0.0000	0.0736
11	10.0	18.90	71.10	0.9847	0.9157	0.0690	0.1042
12	11.0	18.69	70.31	0.9704	0.7448	0.2256	0.1752
13	12.0	18.48	69.52	0.9540	0.5341	0.4199	0.2888
14	13.0	18.27	68.73	0.9358	0.3364	0.5994	0.3867
15	14.0	18.06	67.94	0.9161	0.2532	0.6629	1.0900
16	15.0	17.85	67.15	0.8949	0.1810	0.7139	1.2050
17	16.0	17.64	66.36	0.8724	0.1286	0.7438	1.3134
18	17.0	17.43	65.57	0.8486	0.1218	0.7268	1.3265
19	18.0	17.22	64.78	0.8236	0.1195	0.7041	1.4118
20	19.0	17.01	63.99	0.7972	0.1192	0.6780	1.4339
21	19.5	16.91	63.60	0.7836	0.1000	0.6836	—

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Table. 2

p_0 (kPa)	LFL (% v/v)	UFL (% v/v)
100	3.50	19.00
80	3.75	15.00
60	3.33	14.17
40	3.75	12.50

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485 **Figure captions**

486 Fig. 1 The 20-L explosion spherical vessel (1 = DME, 2 = air).

487 Fig. 2 Determination of the maximum explosion pressure and the combustion time from a
488 typical experimental pressure history.

489 Fig. 3 p_{\max} as a function of DME concentration, compared with Mogi and Horiguchi [25]
490 and adiabatic pressure from equilibrium calculations ($p_0 = 100$ kPa). A curve fit of p_{\max}
491 is also shown in the plot.

492 Fig. 4 p_{\max} as a function of DME concentration, compared with chemical adiabatic pressure
493 from equilibrium calculations at an initial pressure of $p_0 = 80$ kPa. A curve fit of p_{\max} is
494 also shown in the plot.

495 Fig. 5 p_{\max} as a function of DME concentration, compared with adiabatic pressure from
496 equilibrium calculations at an initial pressure of $p_0 = 60$ kPa. A curve fit of p_{\max} is also
497 shown in the plot.

498 Fig. 6 p_{\max} as a function of DME concentration, compared with adiabatic pressure from
499 equilibrium calculations at an initial pressure of $p_0 = 40$ kPa. A curve fit of p_{\max} is also
500 shown in the plot.

501 Fig. 7 Maximum rate of pressure rise as a function of DME concentration for different initial
502 pressures. Curve fits (shown by the solid lines) are also provided to show the trend in
503 the data.

504 Fig. 8 Comparison of the laminar burning velocity from chemical simulation and experiment
505 at an initial pressure of $p_0 = 100$ kPa, Data from Qin and Ju [33] and Daly et al. [4] are
506 also shown for comparison.

507 Fig. 9 Comparison of the laminar burning velocity calculated by detailed reaction kinetic
508 simulations and determined from explosion properties: (a) 80 kPa, (b) 60 kPa; and (c)
509 40 kPa.

510 Fig. 10 Dimensionless radius of burned DME-air mixtures with an equivalent ratio of $\varphi = 1$ at
511 different initial pressures.

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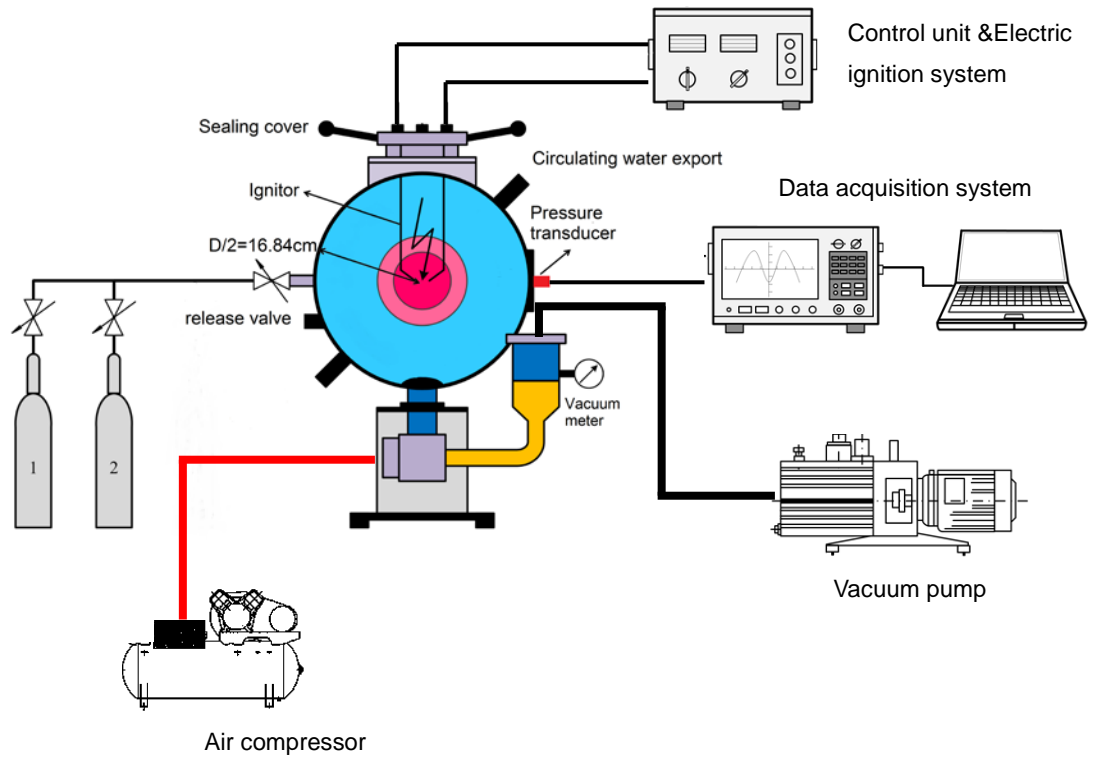
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Fig.1

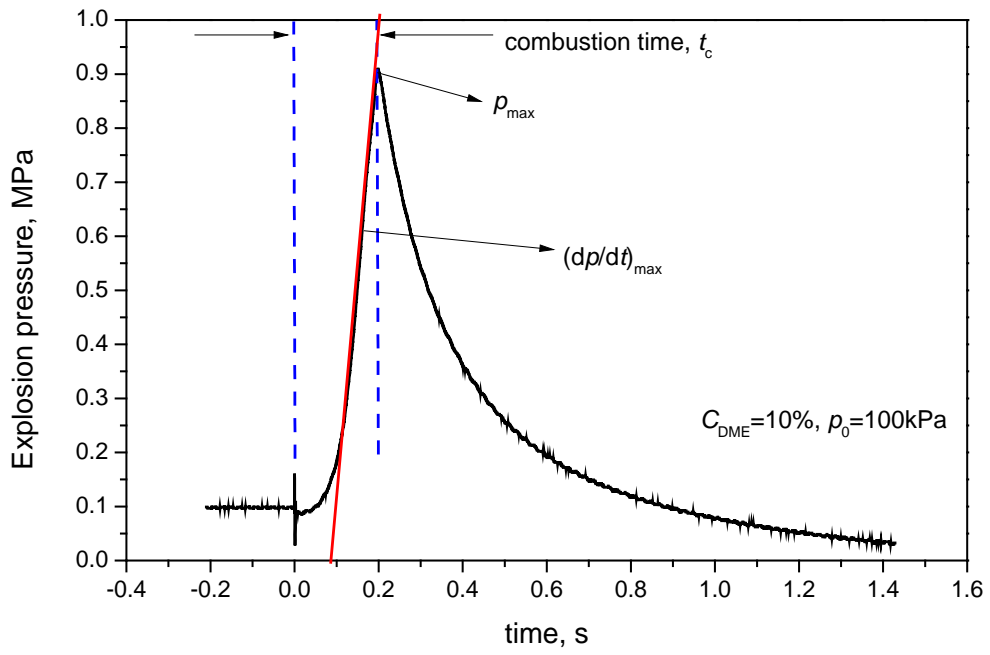
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Fig.2

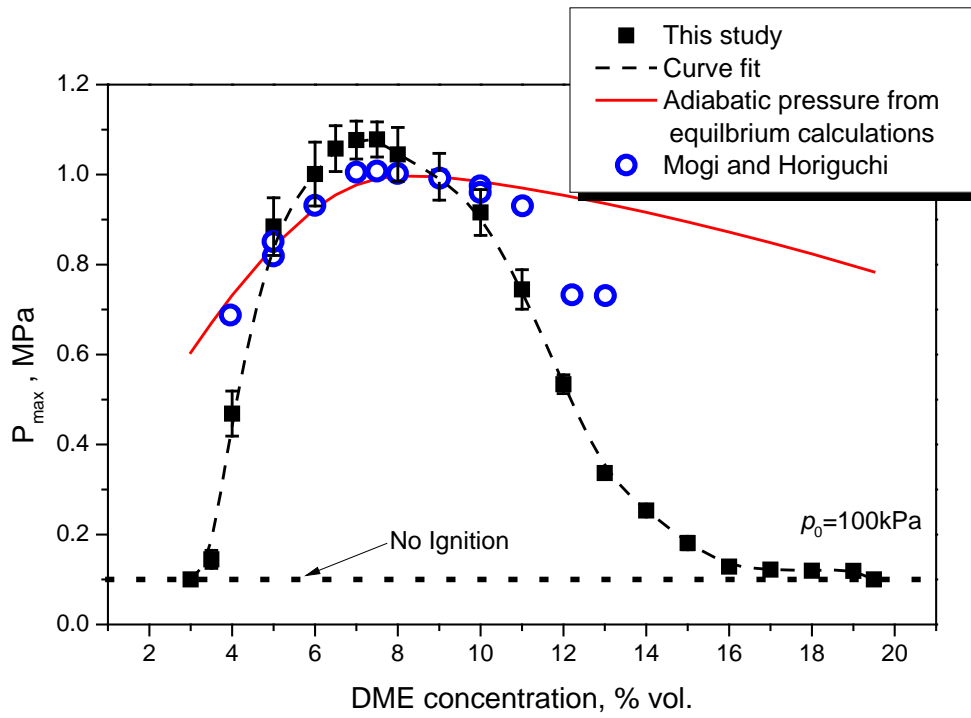
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Fig.3

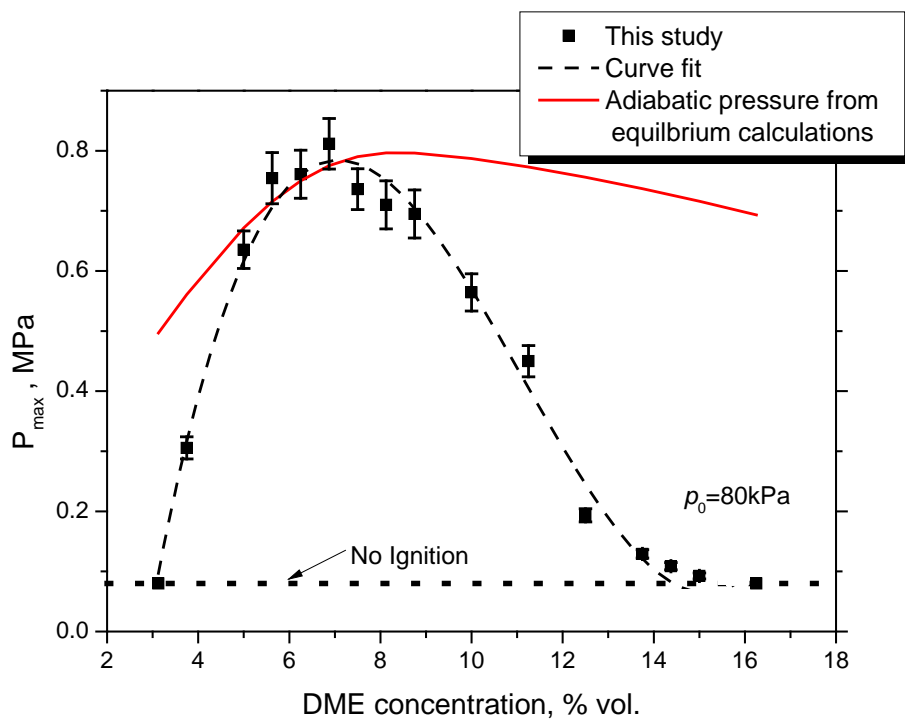
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Fig.4

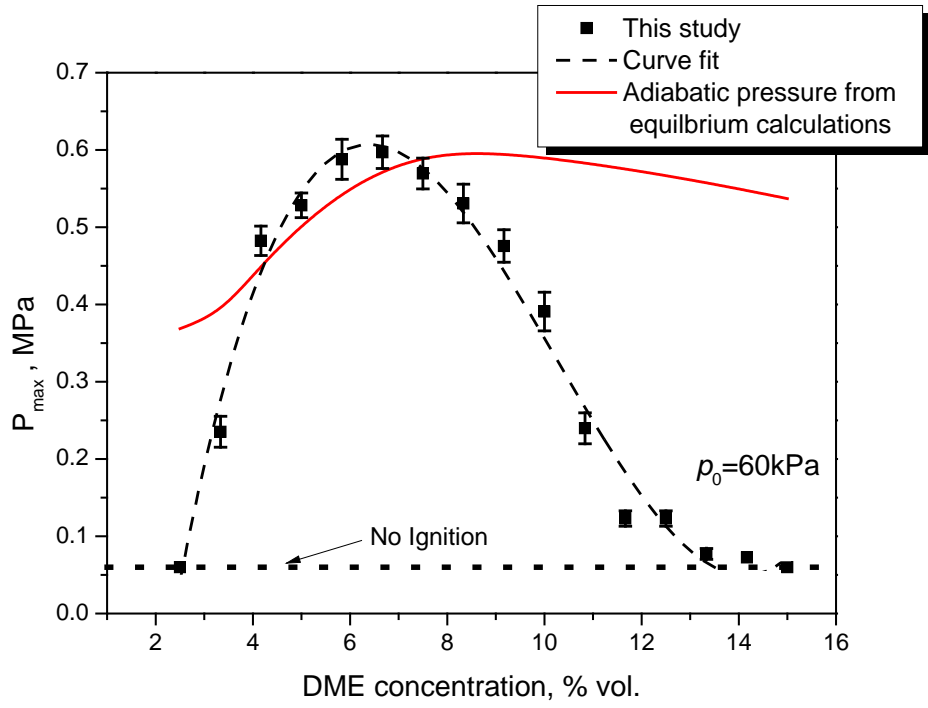
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Fig.5

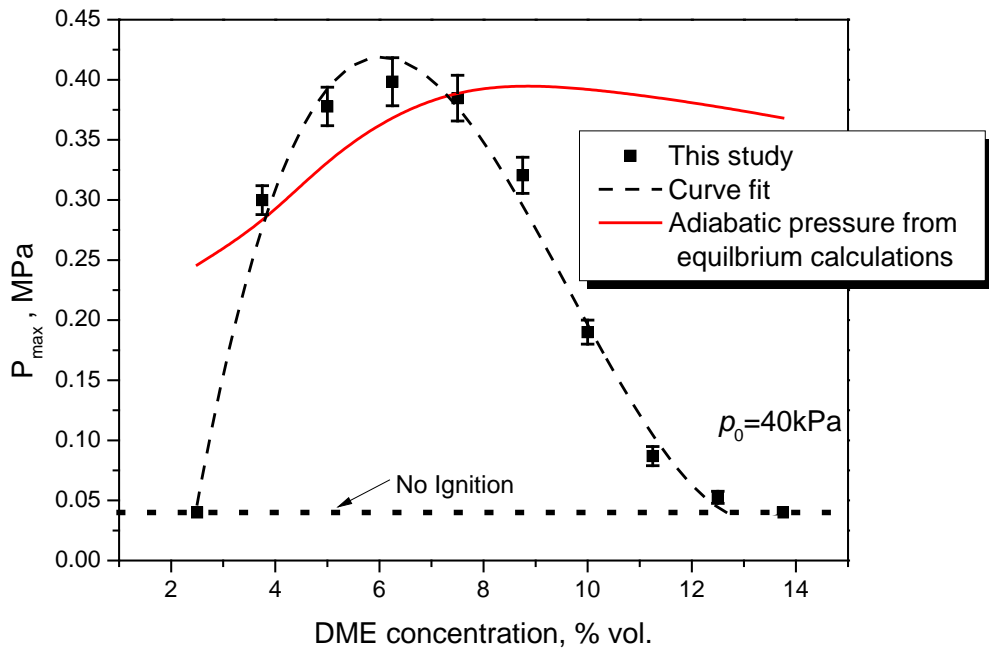
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Fig.6

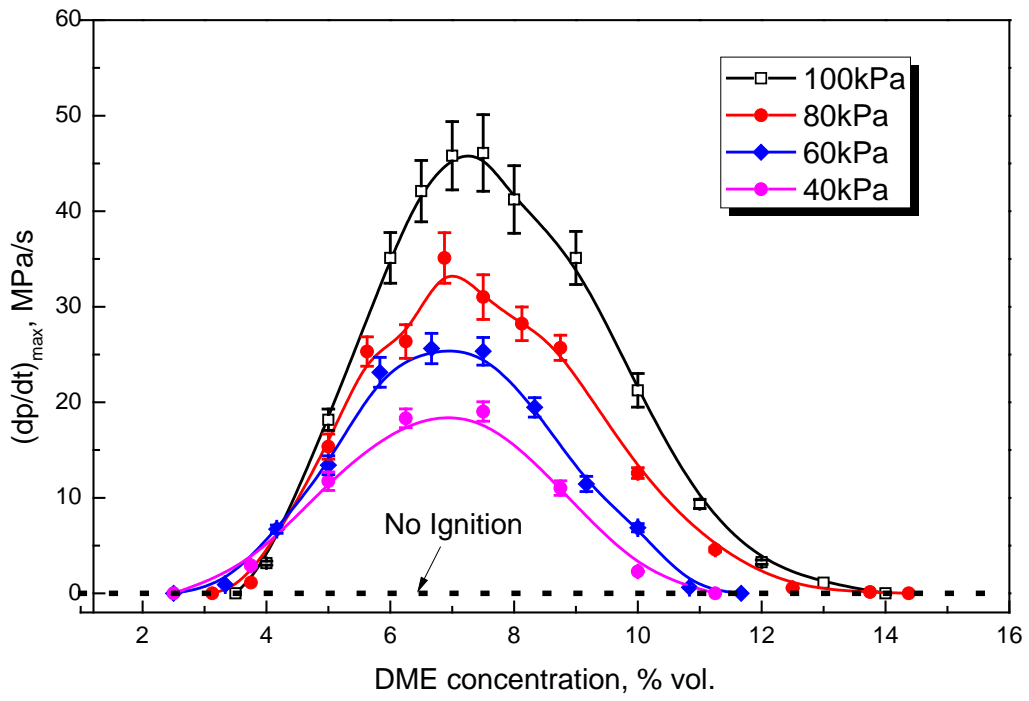
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Fig.7

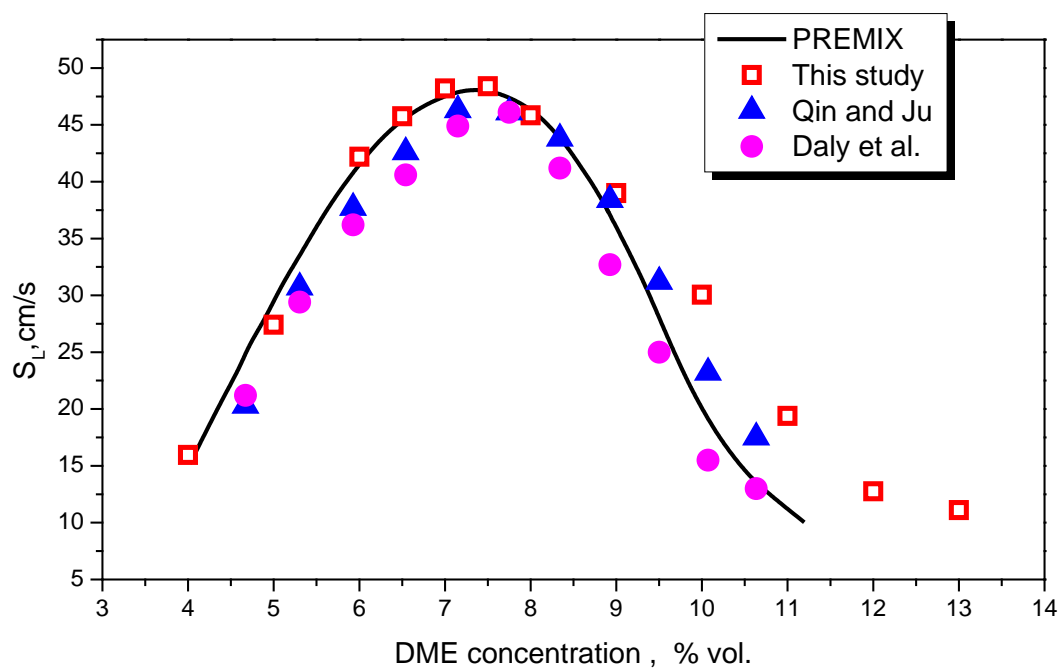
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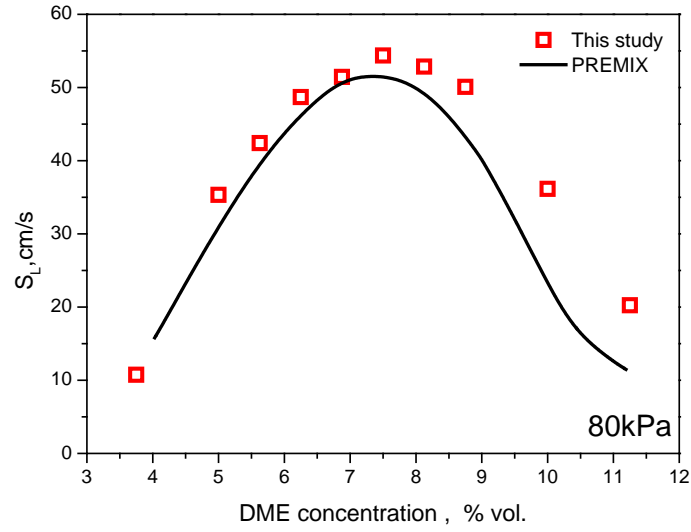
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Fig. 8

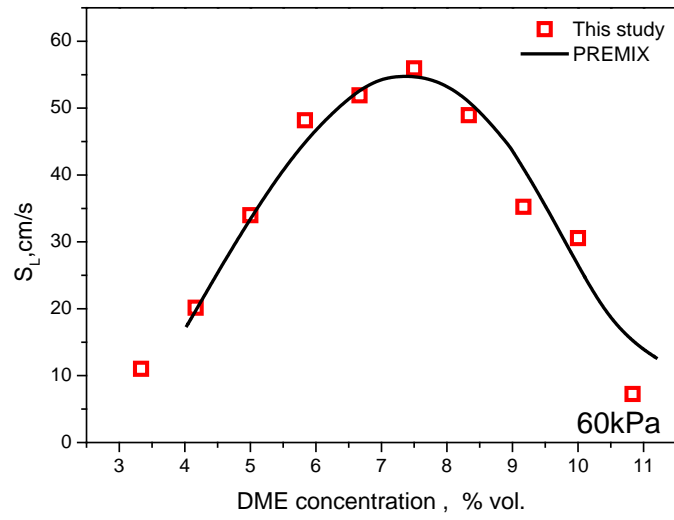
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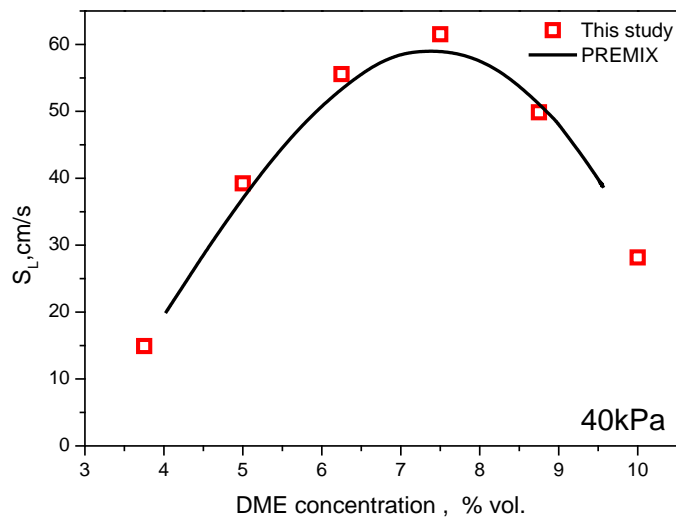
(a)



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(b)



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(c)

Fig.9

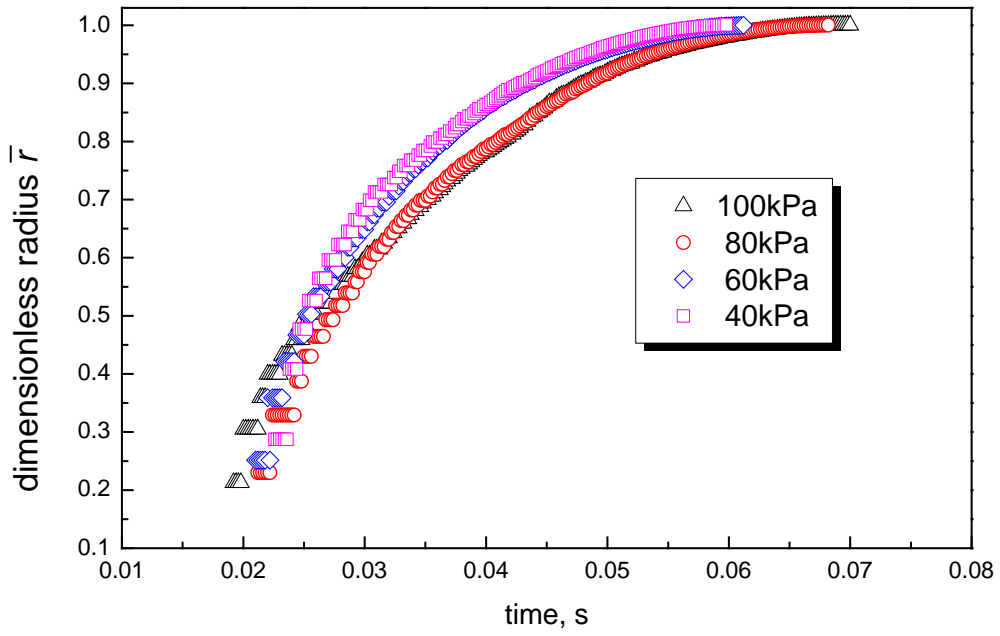
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Fig.10