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Citation: Azimov, Ulugbek, Kawahara, Nobuyuki and Tomita, Eiji (2016) Quantum cascade laser assisted time-resolved measurements of carbon dioxide absorption during combustion in DME-HCCI engine. Fuel, 182. pp. 807-815. ISSN 0016 2361

Published by: Elsevier

URL: <http://dx.doi.org/10.1016/j.fuel.2016.06.040> <<http://dx.doi.org/10.1016/j.fuel.2016.06.040>>

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QUANTUM CASCADE LASER-ASSISTED TIME-RESOLVED MEASUREMENTS OF CARBON DIOXIDE ABSORPTION DURING COMBUSTION IN DME-HCCI ENGINE

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Abstract

We conducted experiments to investigate in-cylinder light absorption by carbon dioxide (CO₂) during homogeneous charge compression ignition (HCCI) engine combustion. The combustion was fuelled with dimethyl ether. An *in situ* laser infrared absorption method was developed. We used an optical fibre spark plug sensor and the light source was a 4.301 μm quantum cascade laser (QCL). We applied Lambert–Beer’s law in the case of a single absorption line of CO₂. We were able to measure the transient CO₂ formation during the HCCI combustion inside the engine cylinder. Our experiments showed that the laser light transmissivity level decreased with the intensity of the infrared (IR) signal. We compared the change in the transmissivity to the spatially integrated HCCI flame luminosity level and observed significant correlations between the flame luminosity level, heat release rate and transmissivity. Time-resolved experiments showed that the CO₂ absorbance increases when the second peak of the rate of heat release (ROHR) is maximised. After combustion, the CO₂ concentration was approximately 4 vol. %, which agrees with the amount of CO₂ formed during complete combustion.

Keywords: HCCI; IC engine combustion; dimethyl ether; CO₂ infrared light absorption; heat release rate; quantum cascade laser

1. Introduction

Homogeneous charge compression ignition (HCCI) engines have received much attention due to their high combustion efficiency and low nitrogen oxide (NO_x) and particulate matter (PM) emission rates. Recent studies on HCCI-based combustion engines have focused on four-stroke

72 engines using conventional or alternative fuels, including dimethyl ether (DME) fuel [1-4]. In
73 HCCI engines, DME fuel exhibits very strong low-temperature kinetic reactions, making it
74 suitable for compression ignition engines. It is a promising alternative fuel due to the fact that it
75 will not contribute to the air-pollution problems caused by soot and NO_x [5], which are emitted
76 by conventional fuels. To improve understanding of the DME oxidation mechanism in an HCCI
77 engine, we conducted experimental kinetic studies to characterise the combustion. One effective
78 way to investigate the DME reaction mechanisms is to use spectral analysis to determine the
79 major active species, especially CO₂ and CO [6-9]. A number of studies have examined CO₂ and
80 CO absorption in a constant volume vessel or reactor. However, few studies have examined CO₂
81 formation and absorption under normal engine conditions. Schultz et al. [10] investigated the
82 impact of ultraviolet (UV) absorption by CO₂ in high-pressure combustion applications. They
83 measured the absorption cross section of CO₂ at combustion temperatures corresponding to
84 wavelengths of 190 nm and found that the measured absorption cross section had a pronounced
85 temperature dependence in the case of CO₂, and that to analyse the absorption by hot combustion
86 products, significant corrections to the UV combustion measurements must be made. Farooq et
87 al. [11] performed high-pressure measurements of CO₂ absorption at wavelengths near 2.7 μm.
88 They concluded that in this wavelength range, as the spectra broaden and blend at high densities,
89 access to discrete transitions is not possible. This makes it difficult to avoid H₂O interference.
90 Hall et al. [12] used broadband infrared radiation from a tungsten halide lamp to analyse the
91 density of CO₂ in the cylinder of a spark-ignited (SI) engine. The CO₂ was measured by the
92 attenuation of the infrared radiation, which occurs due to the excitation of the 2,300cm⁻¹ infrared
93 vibrational-rotational absorption band. Kawahara et al. [13] used infrared laser absorption to
94 conduct cycle-resolved residual gas concentration measurements inside a heavy-duty diesel
95 engine. They were able to quantify the CO₂ concentration in the residual gas and estimate the
96 internal exhaust gas recirculation (EGR) ratio. Residual gas concentrations, especially CO₂ and
97 H₂O, have also been measured *in situ* using infrared absorption techniques [14, 15].
98 Francqueville et al. [15] measured the CO₂ concentration across the combustion chamber in a

99 spark-ignited engine. Grosch et al. [16] performed infrared spectroscopic concentration
100 measurements of CO₂ and gaseous H₂O in environments that are difficult to measure directly
101 using a fibre optical sensor. The mixture of CO₂ and H₂O was analysed spectrally at a
102 wavelength of about 3,700cm⁻¹ for temperatures up to 573 K and pressures up to 1,800 kPa. An
103 optical absorption sensor was used to make quantitative in-cylinder transmission measurements.

104 Optical absorption-based sensors are used to analyse mixture formation in spark-ignited
105 engines. Using these sensors, it is possible to access the cylinder without modifications such as
106 optical windows. As a result, the thermodynamic and mechanical properties of the engine being
107 studied will not be changed by the apparatus, enabling measurements to be made under realistic
108 conditions. The in-cylinder mixture was analysed using optical absorption-based sensors in
109 conjunction with gas sampling probes. Little progress has been made towards the development
110 of practical absorption-based sensors for CO₂ measurements in high-pressure combustion
111 environments. Most previous high-pressure CO₂ sensors used robust telecommunications diode
112 lasers and optical fibre technology in the near-infrared (NIR) 1.3–1.6 μm wavelength region.
113 These sensors accessed weak vibrational bands of CO₂ by direct absorption [22] and used direct
114 absorption spectroscopy [17–19], wavelength modulation spectroscopy (WMS) [20, 21], or NIR
115 hyperspectral sources. To explore the challenges of optical sensor design for high-pressure
116 applications [23], high-pressure measurements of CO₂ absorption have recently been performed
117 near 2.0 μm.

118 The work presented in this paper is motivated by the need for an *in-situ* absorption-based
119 diagnostic for measuring transient CO₂ concentrations in HCCI engine cylinders. Understanding
120 the transient CO₂ formation process may help resolve problems related to knocking combustion
121 [24] and exhaust gas formation [25]. This also aids the design of efficient HCCI engines with
122 precise ignition timing control and a variable valve timing system [26, 27]. The objective of this
123 study was to measure transient CO₂ formation during DME-HCCI combustion. By combining
124 spectroscopy and QCLs, we were able to determine the CO₂ light absorption. Our aim was to
125 characterise the time-resolved spectrum of CO₂ formation. CO₂ formation is a representative

126 indicator of thermal ignition and fuel oxidation during HCCI combustion.

127

128 2. Experimental setup and procedure

129 We used an optical compression–expansion test engine with a single cylinder and a
130 compression ratio of 9.0, as shown in Figure 1 and Table 1, to study DME-fuelled HCCI. The
131 engine crank was driven externally by a 2,000 W induction motor and rotated at a constant rate
132 of 600 rpm. The DME was premixed with gas at a ratio of 20% oxygen to 80% argon at molar
133 proportions equivalent to $\phi = 0.30$. Argon was used instead of nitrogen for two reasons: firstly, to
134 increase the in-cylinder temperature at the end of compression by decreasing the heat capacity of
135 the in-cylinder gas–fuel mixture; and secondly, to initiate HCCI combustion at a significantly
136 lower compression ratio than that used in conventional HCCI engines. The DME–O₂–Ar fuel
137 mixture was supplied to the mixture tank, where it was heated to the temperature $T_{in} = 293$ K,
138 303 K and 310 K and maintained at pressure $P_{in} = 65$ kPa. While the motor was on, the intake
139 valve remained open, and the fuel mixture was sucked into the cylinder and pushed back into the
140 mixture tank. When the thermocouple reading in the mixture tank stabilised, a valve closure
141 signal was sent to a solenoid that activated the valve stopper. The intake valve was closed at
142 around bottom dead centre (BDC), and the fuel mixture was compressed, autoignited, and
143 combusted. Changes in the gas pressure were measured during the compression and expansion
144 strokes using a KISTLER 6052B pressure transducer. Concurrently, sequential HCCI-DME
145 combustion images were recorded by a high-speed camera (MEMRECAM GX-8; Nac Image
146 Technology Inc., Simi Valley, CA, USA) at 10,000 frames per second with a resolution of 640 ×
147 640 pixels. CO₂ absorption was measured by directing laser light from the QCL to the spark plug
148 sensor via optical fibres, and then to the infrared (IR) detector. A QCL is a semiconductor laser
149 that emits light in the mid- to far-infrared portion of the electromagnetic spectrum. Unlike typical
150 interband semiconductor lasers, which emit electromagnetic radiation through the recombination
151 of electron–hole pairs across the material band gap, the QCL is unipolar and laser emission is
152 achieved via intersubband transitions in a repeated stack of semiconductor multiple quantum

153 well heterostructures [28]. A QCL was used as the light source due to its strong absorption, and
154 because no other gas needs to be introduced to the burned gas or fresh mixture. The
155 centre-wavelength of the QCL at 4.301 μm , shown in Figure 2, coincides with the absorption
156 line of CO_2 . This absorption line is caused by the C–O vibrational-rotational band, estimated
157 using the HITRAN database to occur at temperature 900K [29]. The temperature of 900 K is
158 typical in the combustion conditions investigated. Figure 3 shows an optical fibre-embedded
159 spark plug installed into an engine cylinder head (A). The spark plug includes an electrode and a
160 metallic mirror for laser beam reflection. A schematic diagram of the optical spark plug is shown
161 in (B). The light was transmitted through an optical fibre to the spark-plug sensor installed in the
162 combustion chamber and reflected back from the metal mirror of the sensor, passing through an
163 optical fibre again, and finally to the IR detector (P4631; Hamamatsu Photonics K.K.,
164 Hamamatsu, Japan), as shown in Figure 1. A band-pass filter with a centre-wavelength of 4.300
165 μm and full-width at half-maximum (FWHM) of 160 nm was placed in front of the IR detector.

166 The infrared spectral absorbance was determined by applying the Lambert-Beer law to the
167 measured spectral transmission. The Lambert-Beer law relates the attenuation of light to the
168 properties of the material through which the light is traveling. The proportion of the light
169 absorbed will depend on how many molecules it interacts with.

$$170 \quad A(\lambda) = \log_{10} \left[\frac{I_0(\lambda)}{I(\lambda)} \right] = \epsilon c L \quad (1)$$

171 where $A(\lambda)$ is the spectral absorbance, $I_0(\lambda)$ is the intensity in an air-filled environment, $I(\lambda)$ is
172 the intensity in a DME– O_2 –Ar-filled environment, and ϵ , c and L are the molar absorption
173 coefficient, molar concentration, and measurement length, respectively. To use this law, the
174 molar absorption coefficient of the CO_2 was determined for different pressures and temperatures
175 in advance. In our test engine experiments, we simultaneously measured the CO_2 absorption and
176 in-cylinder pressure, and made a high speed camera recording of the combustion. The initial
177 conditions were fixed at $P_{\text{in}} = 65$ kPa, $T_{\text{in}} = 293, 303$ and 310 K, $\phi = 0.3$. Taking into account
178 cyclic variations in the in-cylinder combustion, the resultant combustion intensities were defined

179 as weak, medium and strong. These combustion intensities were defined as the rate of maximum
180 pressure rise with respect to the crank angle. Figure 4 shows the distribution of the maximum
181 pressure rise for different combustion cycles. Weak combustion cycles have a value below 0.05
182 MPa/d θ . Just above this level, there are a few medium-intensity combustion cycles, followed by
183 a large distribution of high-intensity combustion cycles. We determined correlations between the
184 combustion intensity, in-cylinder pressure, ROHR and time-resolved CO₂ absorption.

185

186 3. Results and discussion

187 3.1 IR signal and laser light transmissivity

188 To ensure a valid analysis, we must take particular care because the pressure and temperature
189 inside the engine cylinder change drastically as the piston moves. The purpose of this study was
190 to quantify the history of the CO₂ concentration inside the combustion chamber; therefore, the
191 molar absorption coefficient of the CO₂ had to be determined in advance at different pressures
192 and temperatures. Figure 5 shows an example of the effects of the ambient pressure and
193 temperature on the molar absorption coefficient of CO₂. The temperatures varied between 300
194 and 900 K, while the pressures were between 0.1 and 2.0 MPa. The results were compared with
195 those obtained from the HITRAN database. HITRAN is a high-resolution transmission
196 molecular absorption database. It is a compilation of spectroscopic parameters used to predict
197 and simulate the transmission and emission of light from gaseous substances. The HITRAN
198 database is recognised by many researchers, and is used in many different applications such as
199 transmission simulations, fundamental laboratory spectroscopy studies and combustion physics
200 [29]. Figure 5 shows that the molar absorption coefficient increases as the ambient pressure
201 increases from 0.1 MPa to 1.0 MPa and changes slightly when the pressure level is above 1.0
202 MPa. The measured molar absorption coefficients for the different pressures and temperatures
203 agreed well with the corresponding values in the HITRAN database.

204 The experimental results for the CO₂ absorption in the engine cylinder are shown in Figure 6.
205 This figure indicates that the HCCI combustion process could be divided into two consecutive

206 parts: a low-temperature reaction (LTR) region, and a high-temperature reaction (HTR) region;
 207 both parts were visible on the pressure trace and the rate of heat release curve. The LTR region
 208 was characterised by the low oxidation rate of the DME. We observed that the IR signal strength
 209 is affected by the in-cylinder pressure. We measured the IR detector voltage using an optical
 210 chopper to eliminate the effect of background radiation on the raw IR signal. The raw IR signal
 211 was stable as CO₂ was not absorbed during the compression stroke. CO₂ was formed in the HTR
 212 region. After the HTR region, the baseline of the IR signal rapidly increased and the
 213 transmissivity of the laser light decreased, due to the absorption of laser light with a wavelength
 214 of 4.3 μm by the CO₂ gas. These combined results indicate that the in-cylinder pressure, ROHR,
 215 IR signal and transmissivity due to CO₂ absorption are correlated.

216

217 3.2 Spatially integrated flame luminosity

218 To obtain a qualitative representation of the rate of combustion, we integrated the flame
 219 luminosity over the cross-sectional area of the engine cylinder. The spatial distribution of the
 220 flame luminosity was determined using numerical integration. For a continuous surface $Z =$
 221 $f(x,y)$, $(x,y) \in \sigma$, the volume beneath it can be computed with

$$222 \quad \iint_{(\sigma)} f(x, y) dx dy \quad (2)$$

223 Applying the method for numerical integration, this can be written as

$$224 \quad \iint_{(\sigma)} f(x, y) dx dy = \lim_{\Delta x \rightarrow 0} \lim_{\Delta y \rightarrow 0} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} f(x_i, y_j) \Delta x \Delta y \approx \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} f(x_i, y_j) \Delta x \Delta y \quad (3)$$

225 where M and N are the number of rows and columns of the computational matrix, respectively.

226 In the actual computation, $(f(x_i, y_j) + f(x_i, y_{j+1}) + f(x_{i+1}, y_j) + f(x_{i+1}, y_{j+1}))/4$ was used
 227 instead of $f(x_i, y_j)$.

228 Raw two-dimensional images of the flame intensity in the HTR region are shown on the
 229 left-hand-side of Figures 7–9. These were obtained with a high-speed camera at a fixed
 230 equivalence ratio of 0.3, intake pressure 65 kPa and intake temperatures of 293 K, 303 K and

231 310 K. Combustion appeared as a blue flame; a luminescent flame from soot was not observed.
232 The images on the right-hand-side of Figures 7–9 show the effects of post-processing. The post
233 processing took into account the distribution of flame intensity. The image intensity before the
234 start of mixture autoignition was subtracted from the image intensity during combustion. This
235 eliminated the background light so that only the magnitude of the light emitted from the flame
236 was plotted. There were marked differences between the flame intensities for weak (293 K),
237 medium (303 K) and strong (310 K) combustion cycles. These differences arise from differences
238 in the IR signal strength and the amount of light transmitted due to CO₂ absorption. Figure 7,
239 which corresponds to graph (A) on Figure 6, shows very weak flame intensity. Figures 8 and 9,
240 which respectively correspond to graphs (B) and (C) on Figure 6, show that the distributed
241 reactions appeared to progress inhomogeneously. The inhomogeneity was due to temperature
242 and concentration fluctuations. These observations are in agreement with previous results.
243 Hultqvist et al. [7] used chemiluminescence images and spectra to investigate HCCI combustion
244 processes fuelled using blends of n-heptane and isooctane. They observed that during high
245 temperature heat release, the fuel/air mixture begins to autoignite at arbitrary points throughout
246 the visible area. Dec et al. [30, 31] investigated HCCI isooctane chemiluminescence images
247 obtained from a single-cylinder optical engine and a high-speed intensified camera. High-speed
248 chemiluminescence images show that the HCCI combustion is a progressive process from the
249 hot region to the cold region, even when the fuel and air are fully premixed before intake occurs.
250 This indicates that HCCI combustion is not homogeneous. The authors suggested that the
251 inhomogeneities derive primarily from the natural thermal stratification caused by heat transfer
252 during compression and turbulent transport in the cylinder.

253

254 *3.3 Time-resolved CO₂ absorption*

255 We found that the laser light transmissivity was correlated with the heat release rate during the
256 combustion process. Figure 10 shows that, for a number of experiments, the minimum light
257 transmissivity gradually decreases as the maximum rate of heat release increases. R^2 , the

258 coefficient of determination, has a value 0.82494. This is a statistical measure indicating how
259 well the regression line approximates the real data points. This trend shows the relationship
260 between the in-cylinder pressure, the transmitted light and the energy release during the
261 DME-HCCI combustion process.

262 Using the data for the transmissivity and absorption coefficient, the molar CO₂ concentration
263 was calculated for different experimental conditions. Figure 11 shows a gradual increase in CO₂
264 concentration (B), calculated from absorption data, as the rate of heat release (A) increases
265 during the in-cylinder DME combustion. The peak heat release rate in the LTR region is only
266 slightly different to the rate in the HTR region. The similar levels of heat release in the LTR
267 region occur due to the formation of formaldehyde and the high concentration of H₂O₂, which is
268 further consumed. This facilitates the formation of OH radicals before high-temperature
269 reactions are initiated. Westbrook [32] reported that the H₂O₂ decrease and the OH increase
270 occurred almost simultaneously, and that H₂O₂ decomposition was the initiator of thermal
271 ignition. However, Kuwahara and Ando [33] reported that the decrease in H₂O₂ started earlier
272 than the OH increase, and that the rapid OH increase started during the final stages of this
273 process. Nevertheless, both research groups agreed that the rapid OH increase occurred at the
274 end of the thermal-ignition preparation region. Taking into account these findings, and the results
275 of our experiments, we propose that the CO₂ concentration increases only when
276 high-temperature reactions are initiated.

277 The newly developed CO₂ concentration measurement system, using QCL and optical fibre
278 sensors, enabled us to measure the CO₂ concentration *in situ* during HCCI-DME combustion in a
279 compression-expansion engine. Our results suggest that our CO₂ absorption detection technique
280 gives rise to results that agree with general trends, where CO₂ formation is a product of
281 hydrocarbon fuel combustion. We emphasise that categorising the experimental results by
282 different combustion intensities (weak, medium and strong), as captured by high-speed camera
283 imaging, allowed us to demonstrate that the CO₂ absorption behaviour was directly correlated
284 with the transient in-cylinder combustion characteristics such as pressure, ROHR, light

285 transmissivity and IR signal. Our future work will focus on measuring transient CO₂
286 concentrations under boosted engine conditions.

287 4. Conclusions

288 A new measurement technique was developed based on QCL and optical fibre sensors. Our
289 technique enables the *in situ* measurement of transient CO₂ concentrations during DME-HCCI
290 combustion. We draw the following conclusions:

291 1. Lambert–Beer’s law was **applied** for the case of a single absorption line of CO₂. Using a
292 constant volume vessel, the relationship between the ambient pressure, temperature and the CO₂
293 molar absorption coefficient was determined. The coefficient increased as the pressure increased
294 up to 1.0 MPa, where the rate of increase slowed dramatically.

295 2. The laser light transmissivity was correlated with the heat release rate during the combustion
296 process. In some experiments, the minimum light transmissivity decreased gradually as the
297 maximum rate of heat release increased.

298 3. The time-resolved CO₂ absorption profiles during the DME–O₂–Ar mixture combustion under
299 a range of conditions indicated that the CO₂ absorbance increases only in the high-temperature
300 reaction region.

301 4. There were marked differences in the intensity of the emissions in different combustion cycles
302 with identical initial conditions. The number, intensity, and size of hot spots in those cycles
303 varied significantly due to combustion cyclic variations, leading to the observation of very
304 inhomogeneous patterns.

305

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310 References

311 [1] Takatsuto R, Igarashi T, Iida N. Auto-ignition and combustion of DME and n-Butane/air
312 mixtures in homogeneous charge compression ignition engine. in: Proceedings of the 4th

- 313 International Symposium COMODIA 1998:185-90.
- 314 [2] Perrson H, Hultqvist A, Johansson B. Investigation of the early flame development in spark
315 assisted HCCI combustion using high speed chemiluminescence imaging. SAE Paper
316 2007-01-0212; 2007.
- 317 [3] Flowers DL, Killingsworth NJ, Espinosa-Loza F, Martinez-Frias J, Aceves SM, Krstic M,
318 Dibble R. Demonstrating Optimum HCCI Combustion with Advanced Control Technology.
319 SAE Paper 2009-01-1885; 2009.
- 320 [4] Manente V, Zander C, Johansson B, Tunesta P, Cannella W. An advanced internal combustion
321 engine concept for low emissions and high efficiency from idle to max load using gasoline
322 partially premixed combustion. SAE Paper 2010-01-2198; 2010.
- 323 [5] Arcoumanis C, Bae C, Crookes R, Kinoshita E. The potential of di-methyl ether (DME) as an
324 alternative fuel for compression-ignition engines: a review. Fuel 87; 2008:1014-30.
- 325 [6] Iida N. Combustion analysis of methanol-fueled active thermo-atmosphere combustion
326 (ATAC) engine using a spectroscopic observation. SAE Paper 940684; 1984.
- 327 [7] Hultqvist A, Cristensen M, Johansson B, Richter M, Alden M. A study of the homogeneous
328 charge compression ignition combustion process by chemiluminescence imaging. SAE
329 Paper 1999-01-3680; 1999.
- 330 [8] Kim B, Kaneko M, Ikeda Y, Nakajima T. Detailed spectral analysis of the process of HCCI
331 combustion. Proc Combust Inst 2002;29:671-677.
- 332 [9] Iijima A, Yoshida K, Shoji H. A study of autoignition in an HCCI engine by using light
333 absorption and emission spectroscopy in: Proceedings of the 7th International Symposium
334 COMODIA 2008: 297-303.
- 335 [10] Schultz C, Jeffries JB, Davidson DF, Kocj JD, Wolfrum J, Hanson RK. Impact of UV
336 absorption by CO₂ and H₂O on NO LIF in high-pressure combustion applications. Proc
337 Combust Inst 2002;29:2735-2742.
- 338 [11] Farooq A, Jeffries JB, Hanson RK. High-pressure measurements of CO₂ absorption near 2.7
339 μm: Line mixing and finite duration collision effects. J Quant Spectrosc Radiat Transfer
340 2010;111:949-960.
- 341 [12] Hall MJ, Zuzek P. Fiber Optic sensor for time-resolved measurements of exhaust gas
342 recirculation in engines. SAE Paper 2000-01-2865; 2000.
- 343 [13] Kawahara N, Tomita E, Ohtsuki A, Aoyagi Y. Cycle-resolved residual gas concentration
344 measurement inside a heavy-duty diesel engine using infrared laser absorption. Proc
345 Combust Inst 2011;33:2903-2910.
- 346 [14] Hall MJ, Zuzek P, Anderson RW. Fiber optic sensor for crank angle resolved measurements
347 of burned gas residual fraction in the cylinder of an SI engine. SAE Paper
348 2001-01-1921;2001.
- 349 [15] Francqueville LD, Thirouard B, Ricordeau V. Measurement of residual gas fraction using IR
350 absorption. SAE Paper 2006-01-3337; 2006.
- 351 [16] Grosch A, Wackerbarth H, Thiele O, Berg T, Beckmann L. Infrared spectroscopic
352 concentration measurements of carbon dioxide and gaseous water in harsh environments

- 353 with a fiber optical sensor by using the HITEMP database. *J Quant Spectrosc Radiat*
354 *Transfer* 2014;133:106-116.
- 355 [17] Sanders ST, Baldwin JA, Jenkins TP, Baer DS, Hanson RK, Diode-laser sensor for
356 monitoring multiple combustion parameters in pulse detonation engines. *Proc Combust Inst*
357 2000;28:587–94.
- 358 [18] Mattison DW, Jeffries JB, Hanson RK, Steeper RR, De Zilwa S, Dec JE, Sjöberg M, Hwang
359 W. In-cylinder gas temperature and water concentration measurements in HCCI engines
360 using a multiplexed-wavelength diode-laser system: Sensor development and initial
361 demonstration. *Proc Combust Inst* 2007;31:791–8.
- 362 [19] Schlosser TFE, Teichert H, Ebert V. In-situ-detection of potassium atoms in
363 high-temperature coal-combustion systems using near-infrared-diode lasers. *Spectrochimica*
364 *Acta* 2002;58:2347–59.
- 365 [20] Fernholz T, Teichert H, Ebert V. Digital, phase-sensitive detection for in situ diode-laser
366 spectroscopy under rapidly changing transmission conditions. *Applied Physics B: Lasers*
367 *and Optics* 2002;75:229–36.
- 368 [21] Rieker GB, Li H, Liu X, Liu JTC, Jeffries JB, Hanson RK, et al. Rapid measurements of
369 temperature and H₂O concentration in IC engines with a spark plug-mounted diode laser
370 sensor. *Proc Combust Inst* 2007;31:3041–9.
- 371 [22] Kranendonk LA, Walewski JW, Kim T, Sanders ST. Wavelength-agile sensor applied for
372 HCCI engine measurements. *Proc Combust Inst* 2005;30:1619–27.
- 373 [23] Rieker G, Jeffries J, Hanson R. Measurements of high-pressure CO₂ absorption near 2.0mm
374 and implications on tunable diode laser sensor design. *Applied Physics B:Lasers and Optics*
375 2009;94:51–63.
- 376 [24] Eng JA. Characterization of pressure waves in HCCI combustion. *SAE Paper* 2002-01-2859;
377 2002.
- 378 [25] Dubreuil A, Foucher F, Mounaim-Rousselle C, Dayma G, Dagaut P. HCCI combustion:
379 Effect of NO in EGR. *Proc Combust Inst* 2007;31:2879–2886.
- 380 [26] Ebrahimi K and Koch CR. HCCI combustion timing control with variable valve timing.
381 American Control Conference (ACC) Washington, DC, USA, June 17-19, 2013
- 382 [27] Saigaonkar H, Nazemi M, Shahbakhti M. Sequential model for residual affected HCCI with
383 variable valve timing. *SAE Paper* 2015-01-1748; 2015.
- 384 [28] Kazarinov RF, Suris RA. Possibility of amplification of electromagnetic waves in a
385 semiconductor with a superlattice. *Fizika i Tekhnika Poluprovodnikov* 1971;5:797–800.
- 386 [29] Rothman LS, Rinsland CP, Goldman A, S.T. Massie ST, Edwards DP, Flaud JM, Perrin A,
387 Camy-Peyret C, Dana V, Mandin JY, Schroeder J, Mccann A, Gamache RR, Wattson RB,
388 Yoshino K, Chance KV, Jucks KW, Brown LR, Nemtchinov V, Varanasi P. The HITRAN
389 molecular spectroscopic database and HAWKS (HITRAN atmospheric workstation): 1996
390 Edition. *J. Quant. Spectrosc. Radiat. Transfer* 1998;60:665-710.
- 391 [30] Dec JE, Hwang W and Sjöberg M. An investigation of thermal stratification in HCCI
392 engines using chemiluminescence imaging. *SAE Paper* 2006-01-1518, 2006.
- 393 [31] Hwang W, Dec J and Sjöberg M. Spectroscopic and chemical-kinetic analysis of the phases

- 394 of HCCI autoignition and combustion for single- and two-stage ignition fuels. *Combust*
395 *Flame* 2008;154, 387–409.
- 396 [32] Westbrook CJ. Chemical kinetics of hydrocarbon ignition in practical combustion systems.
397 *Proc Combust Inst* 2000;28:1563-77.
- 398 [33] Kuwahara K, Ando H. Role of heat accumulation by reaction loop initiated by H₂O₂
399 decomposition for thermal ignition. SAE Paper 2007-01-0908; 2007.

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Table 1

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Bore	78 mm
Stroke	85 mm
Connecting rod length	153 mm
Displacement volume	406.2 cm ³
Compression ratio	9.0:1
Combustion chamber	Pancake type
Engine speed	600 rpm
Valve closure time	180 deg. BTDC

Figure 1
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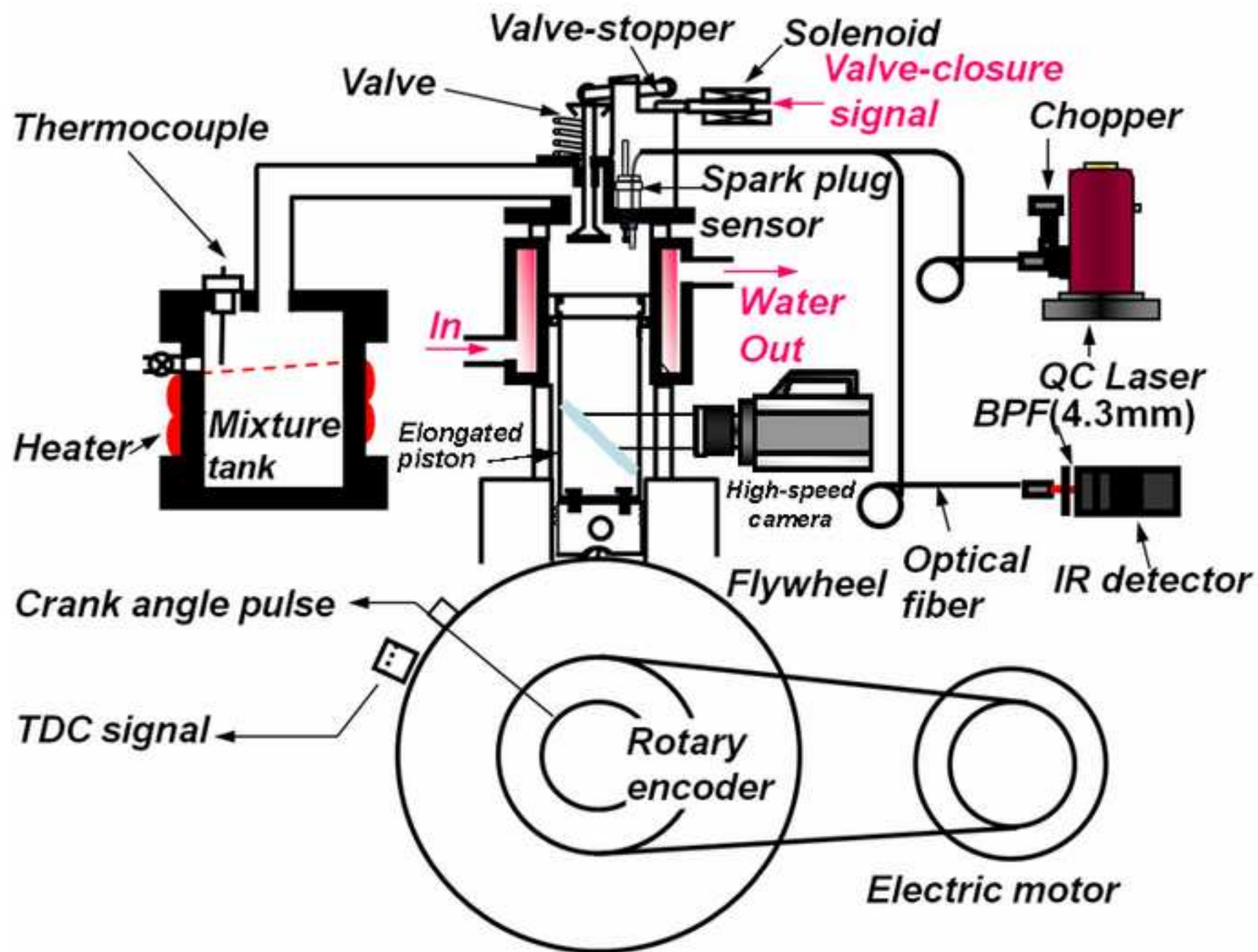


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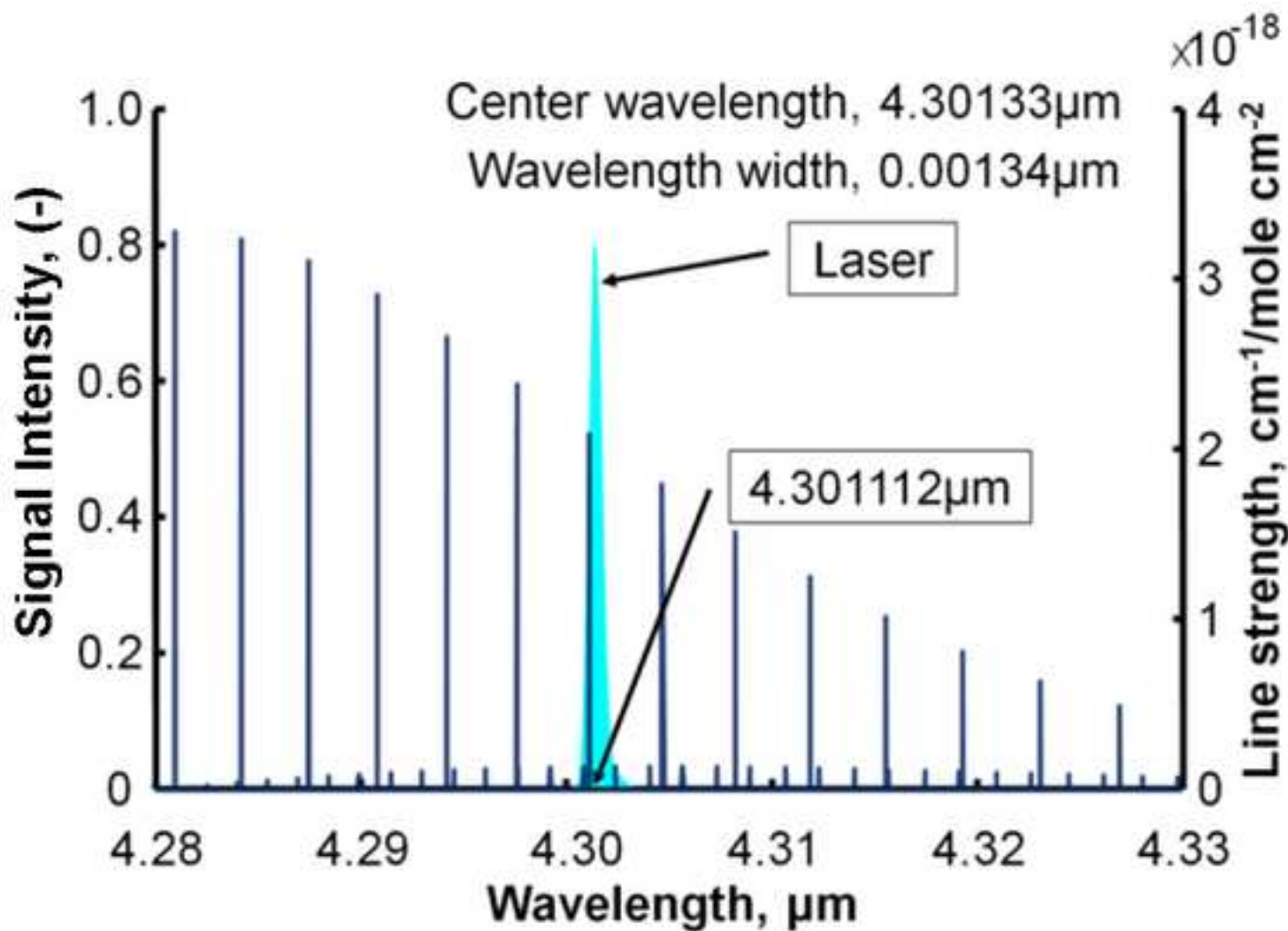


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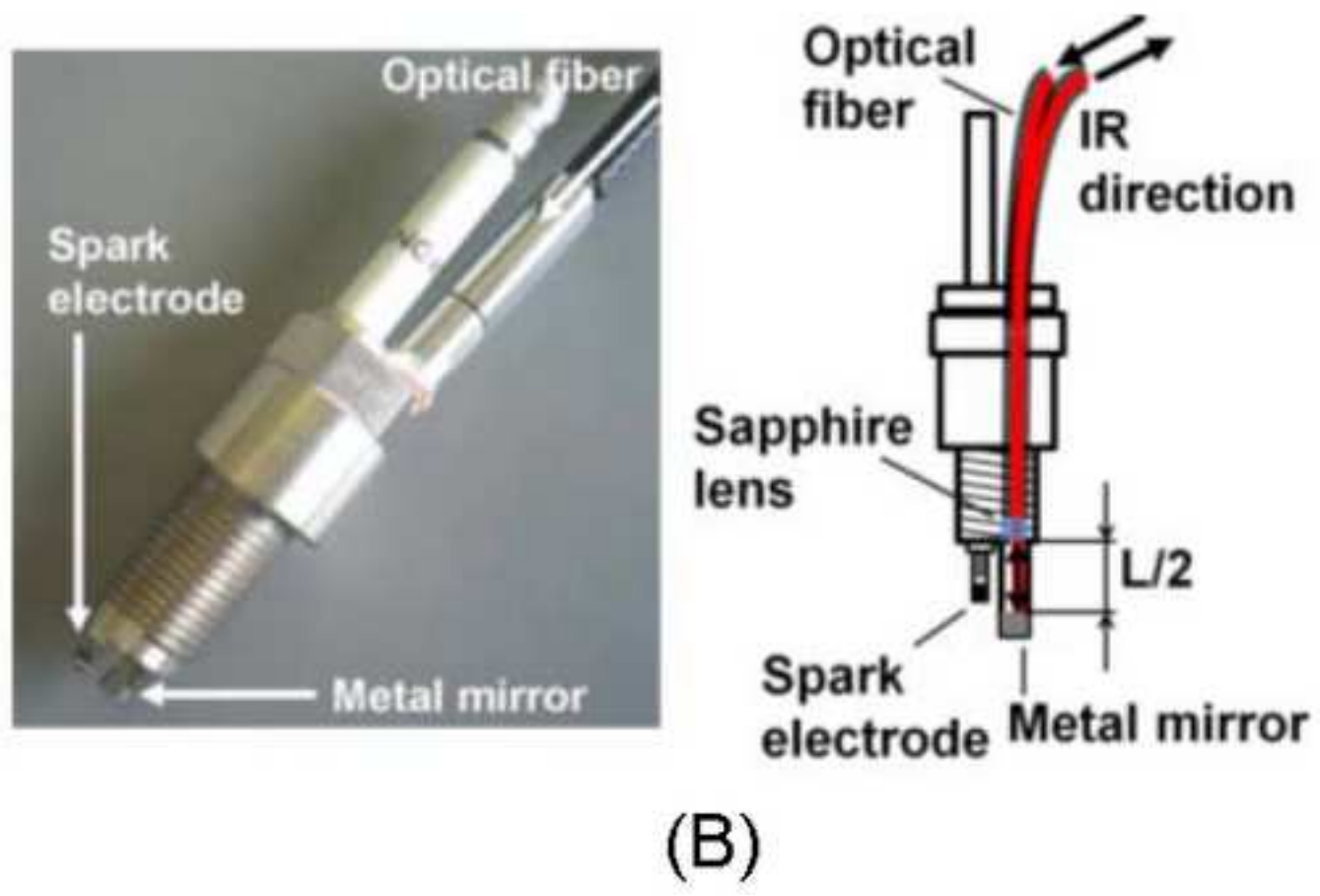
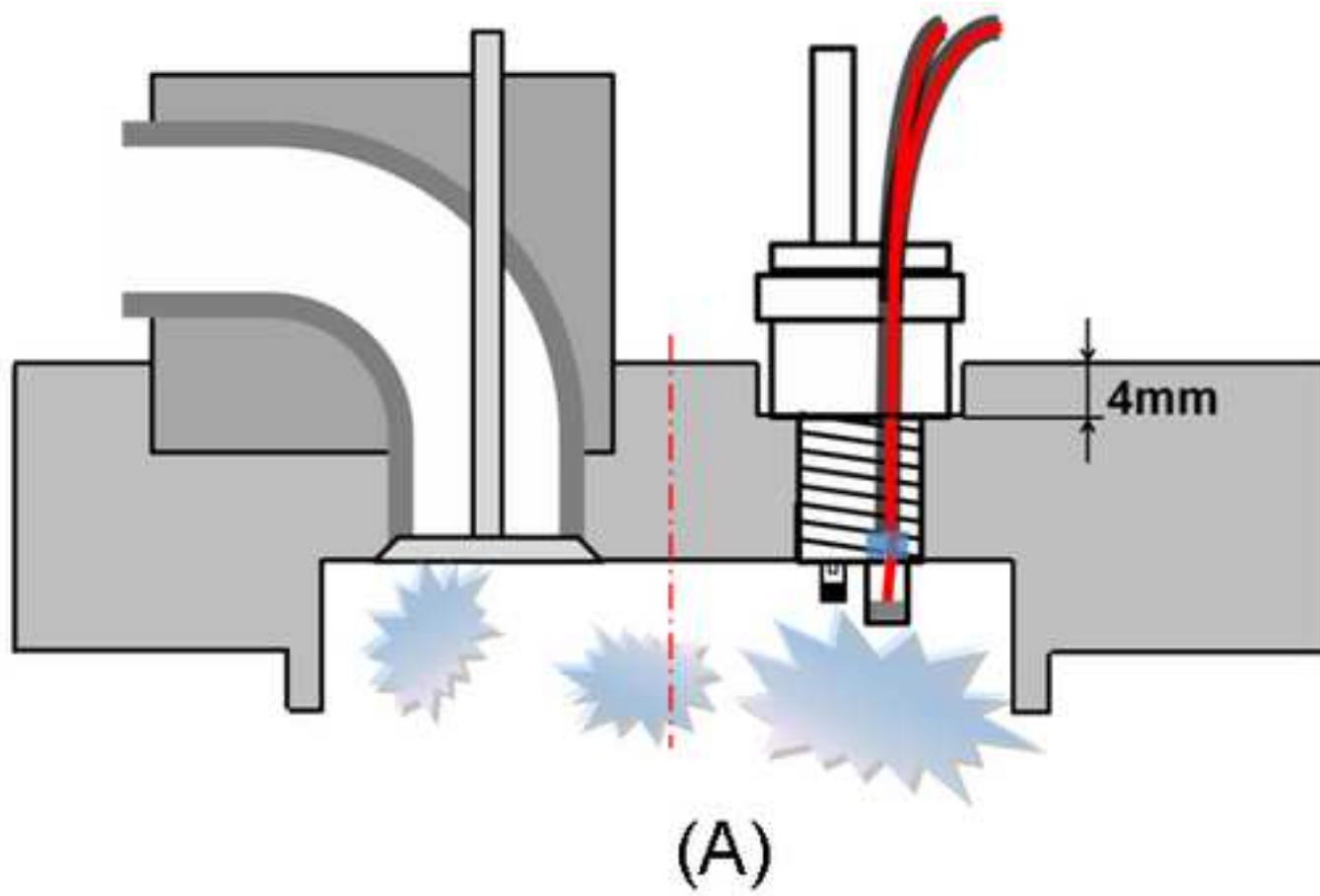


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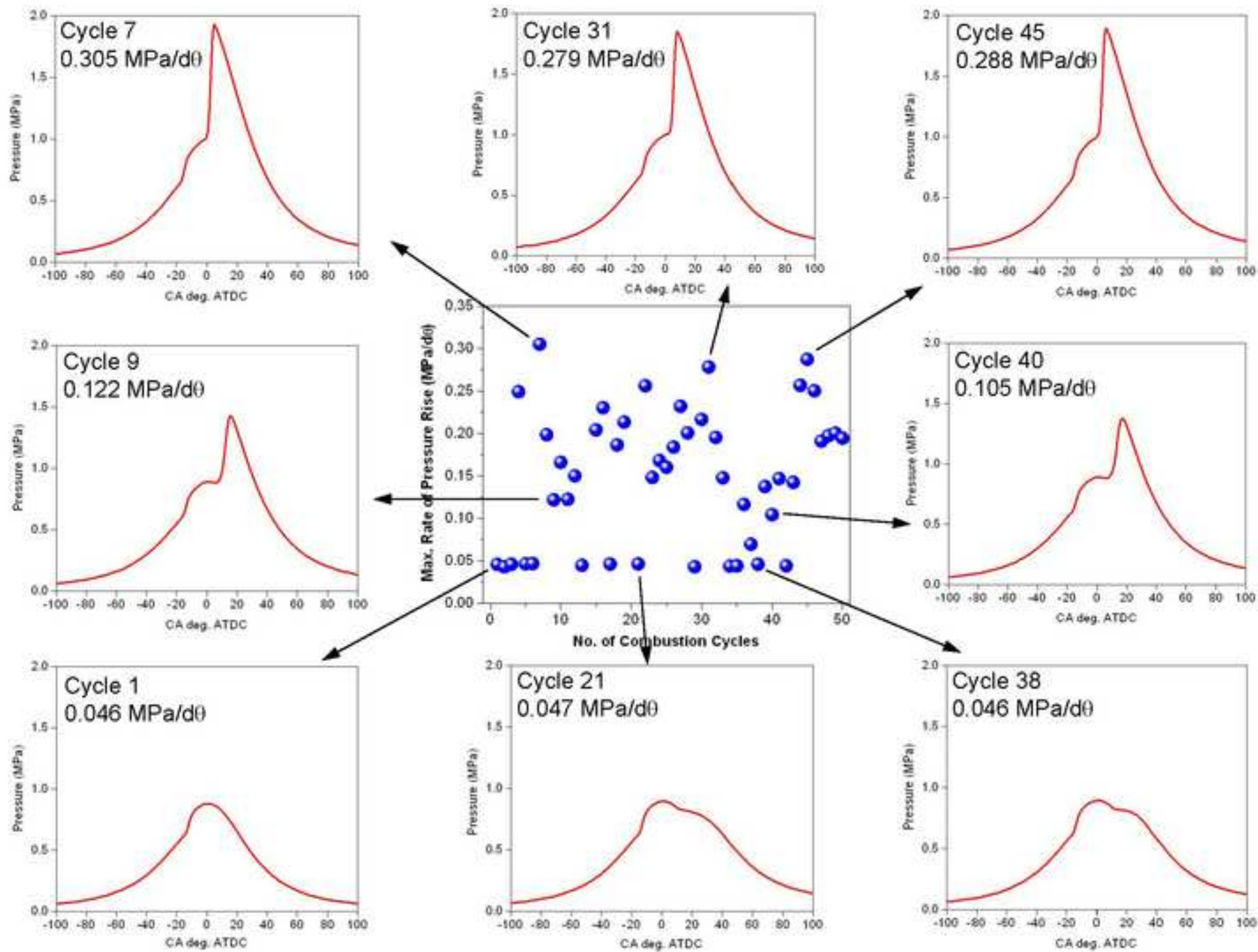


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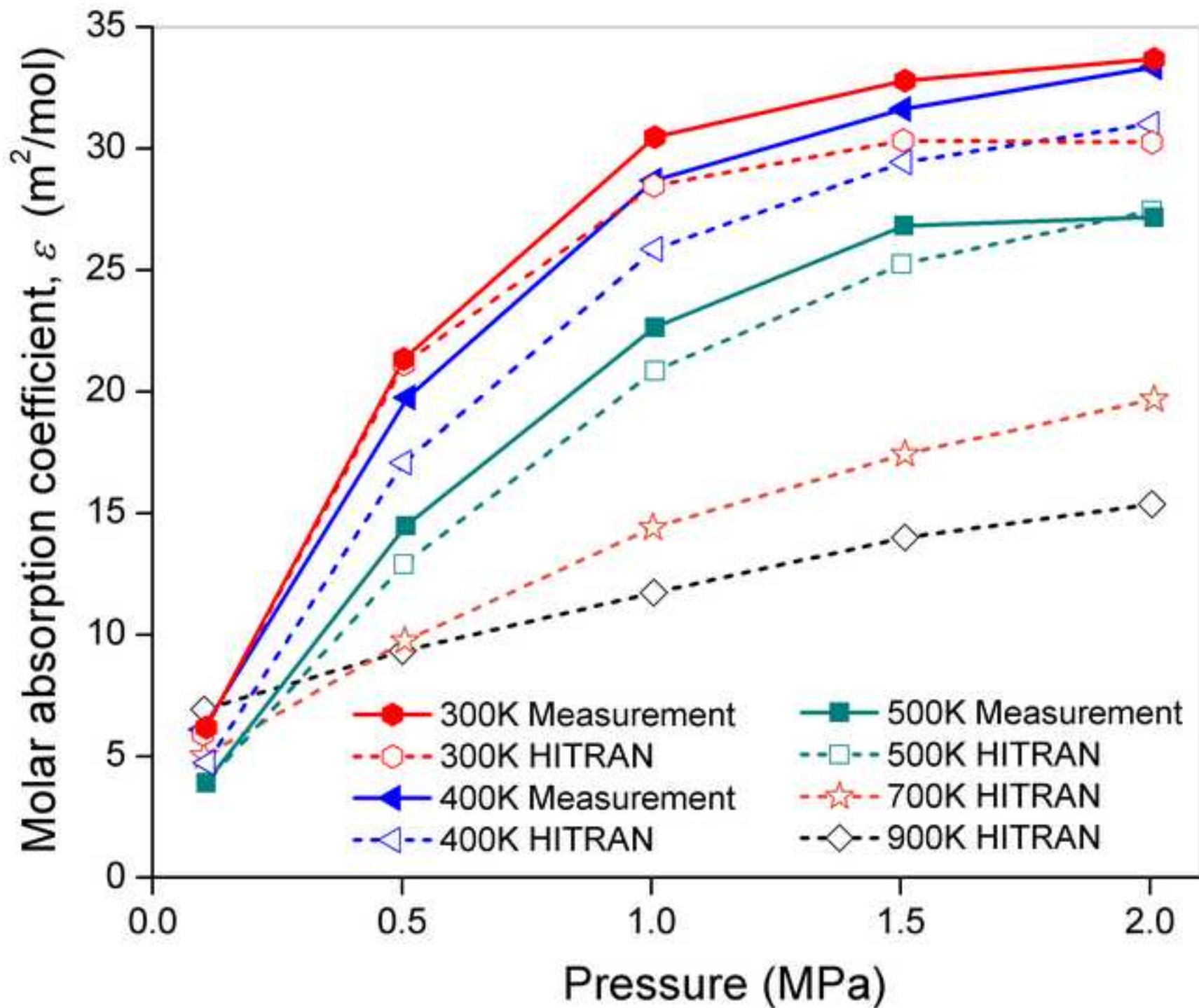


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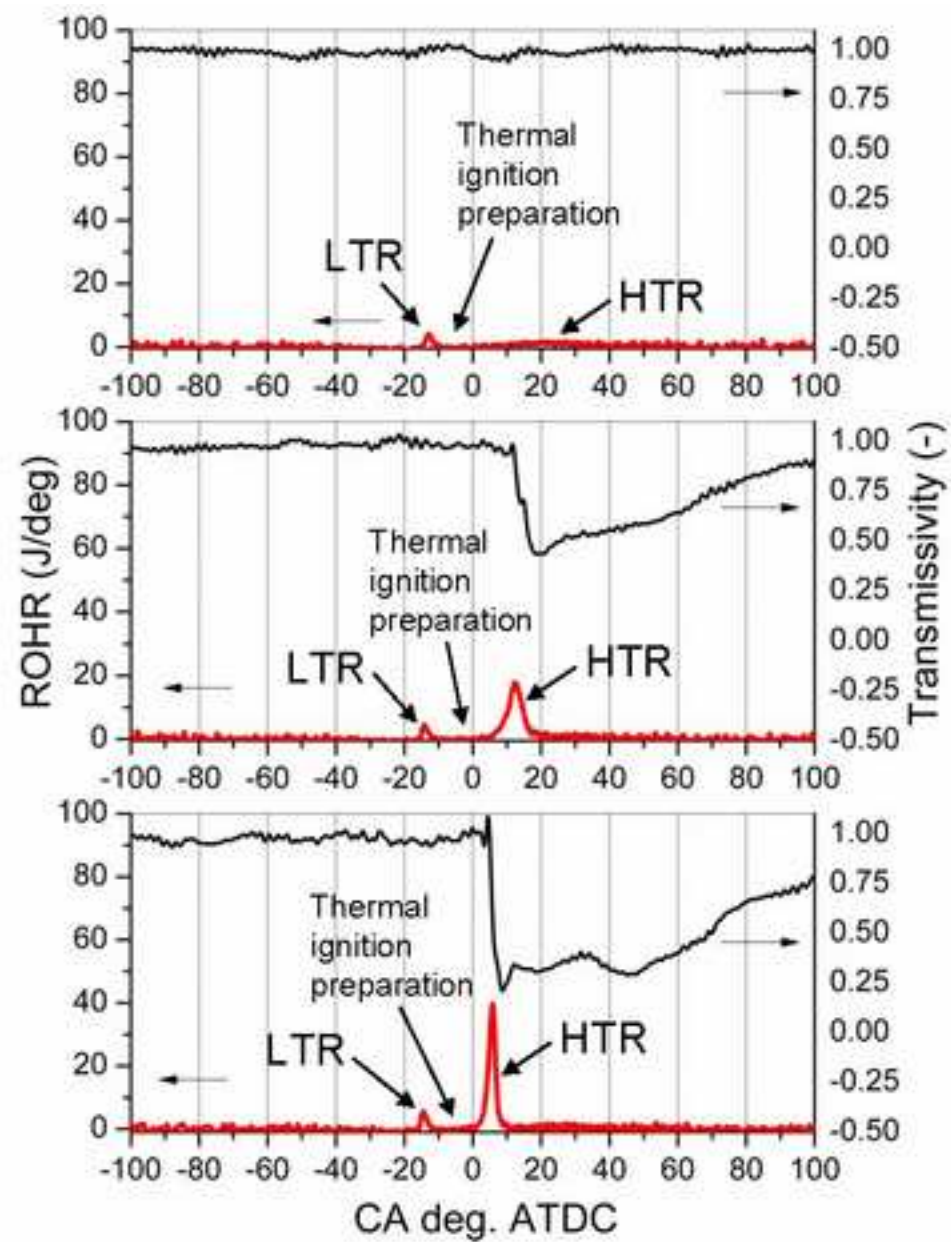
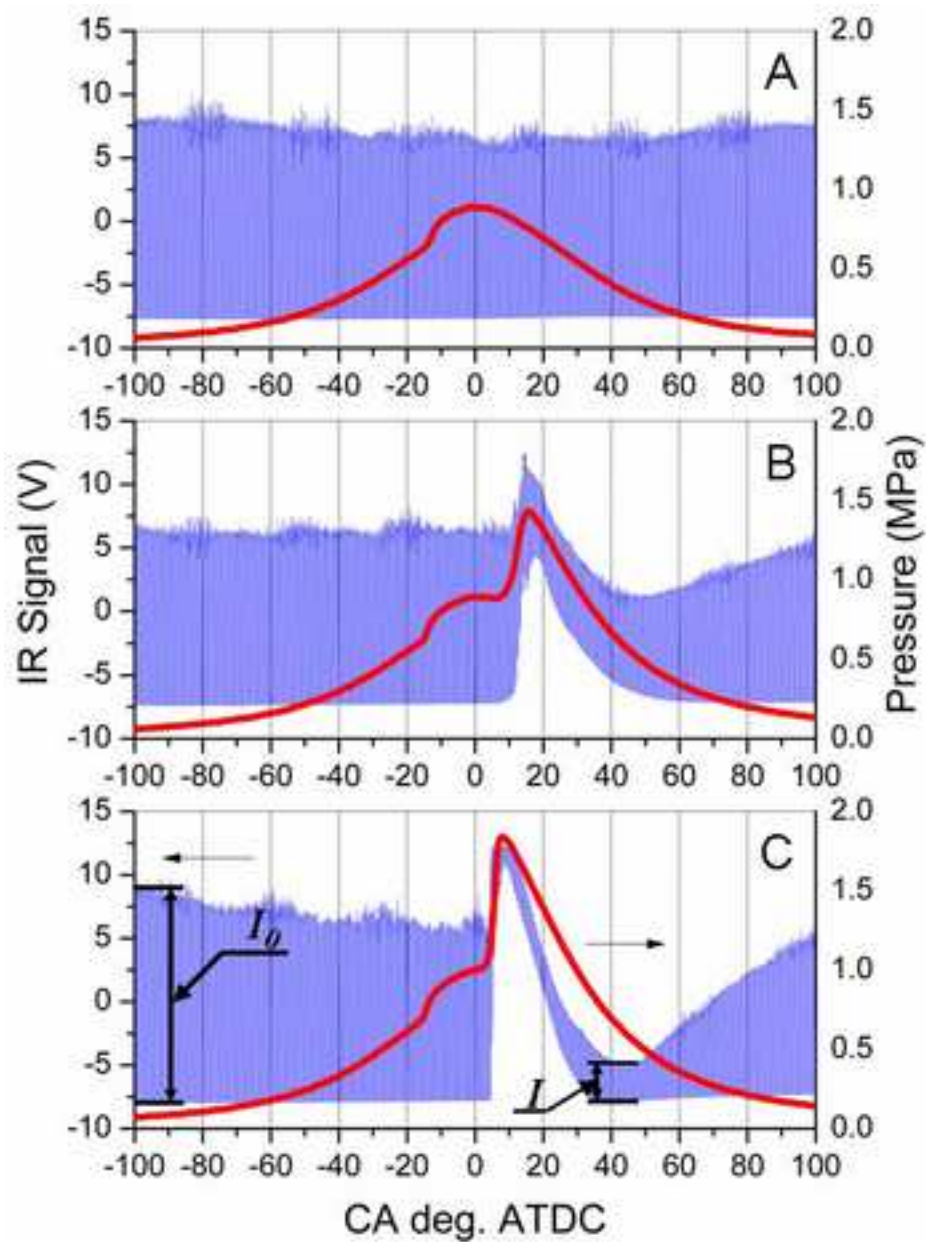
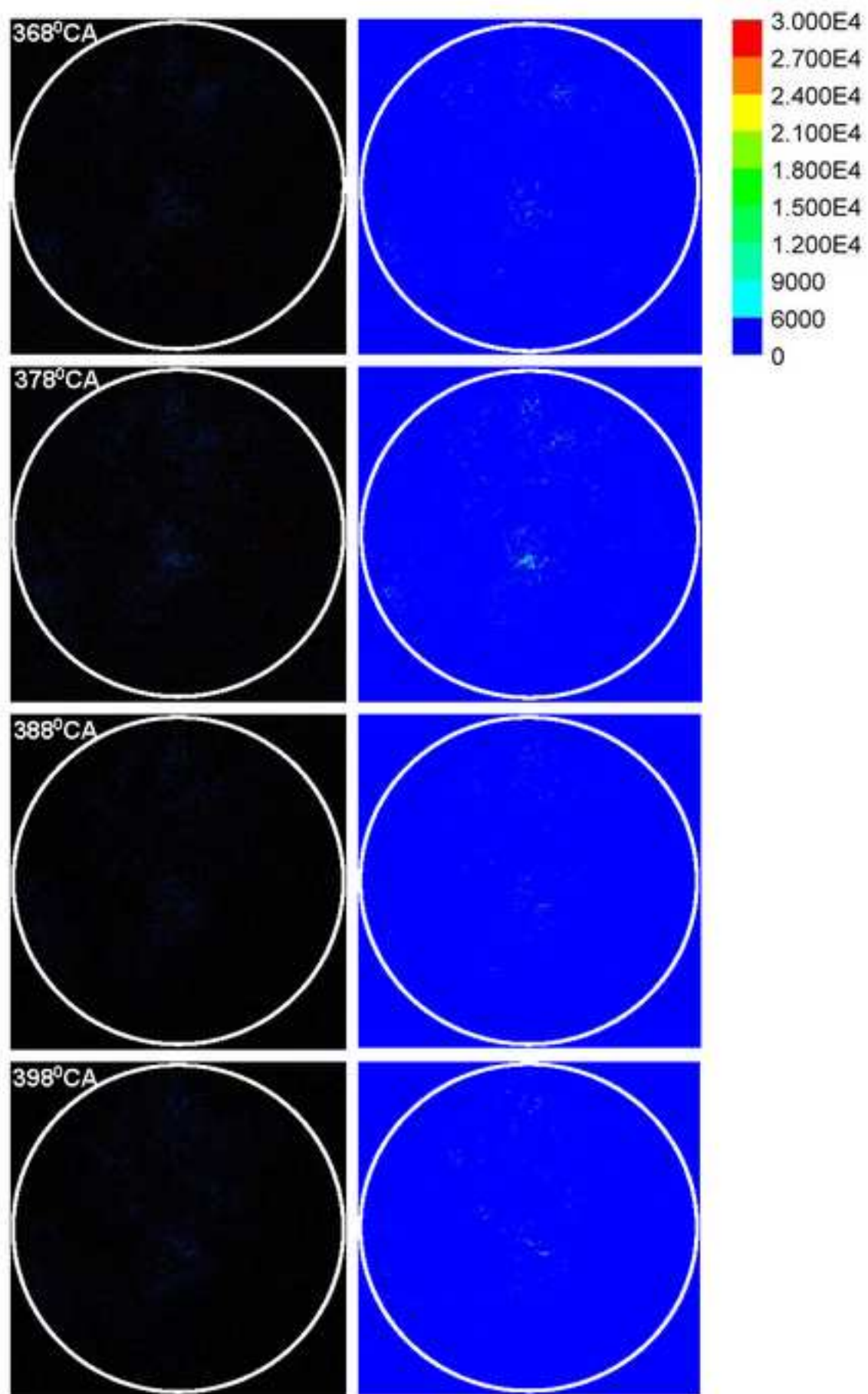


Figure 7

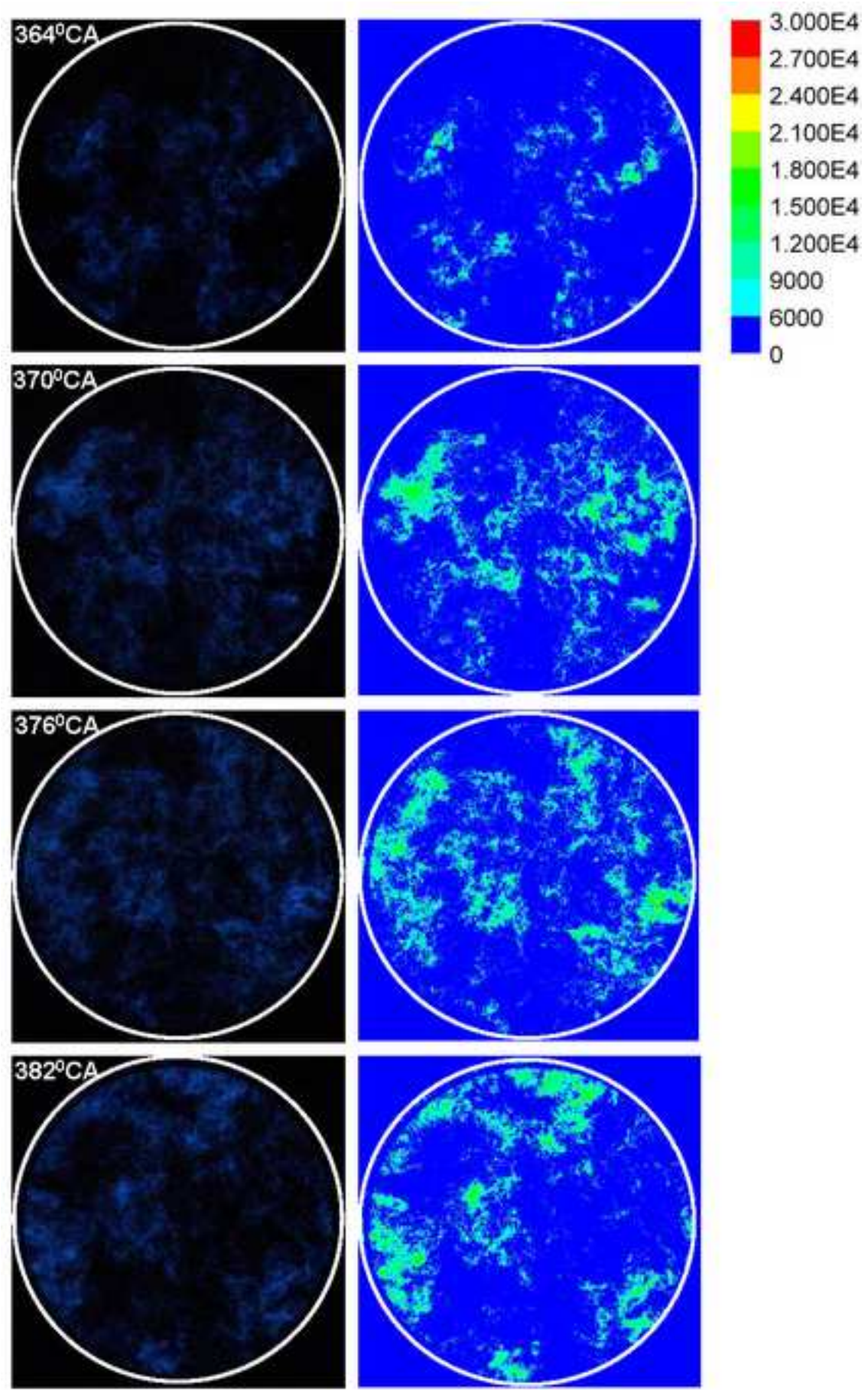
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(A)

Figure 8

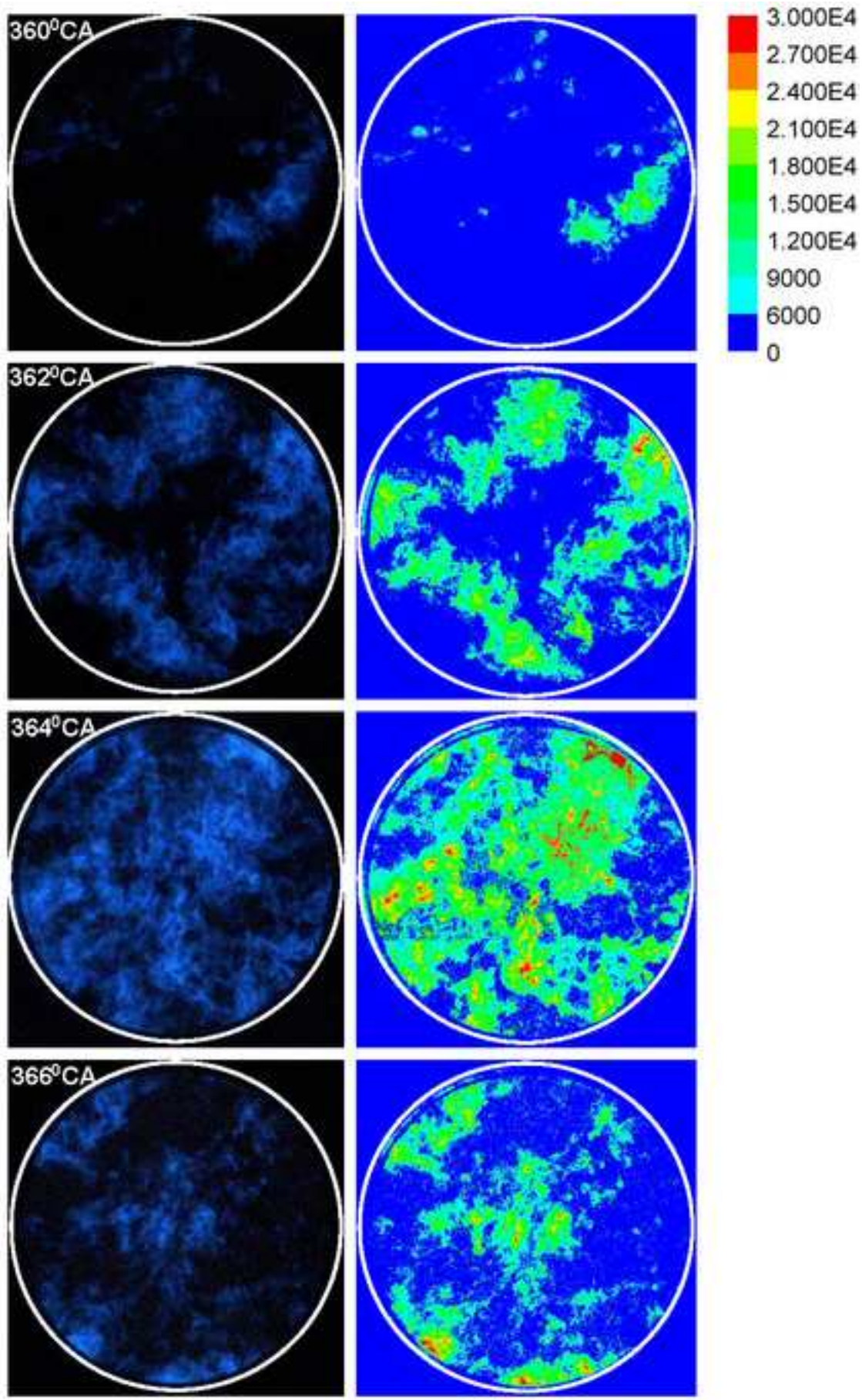
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(B)

Figure 9

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(C)

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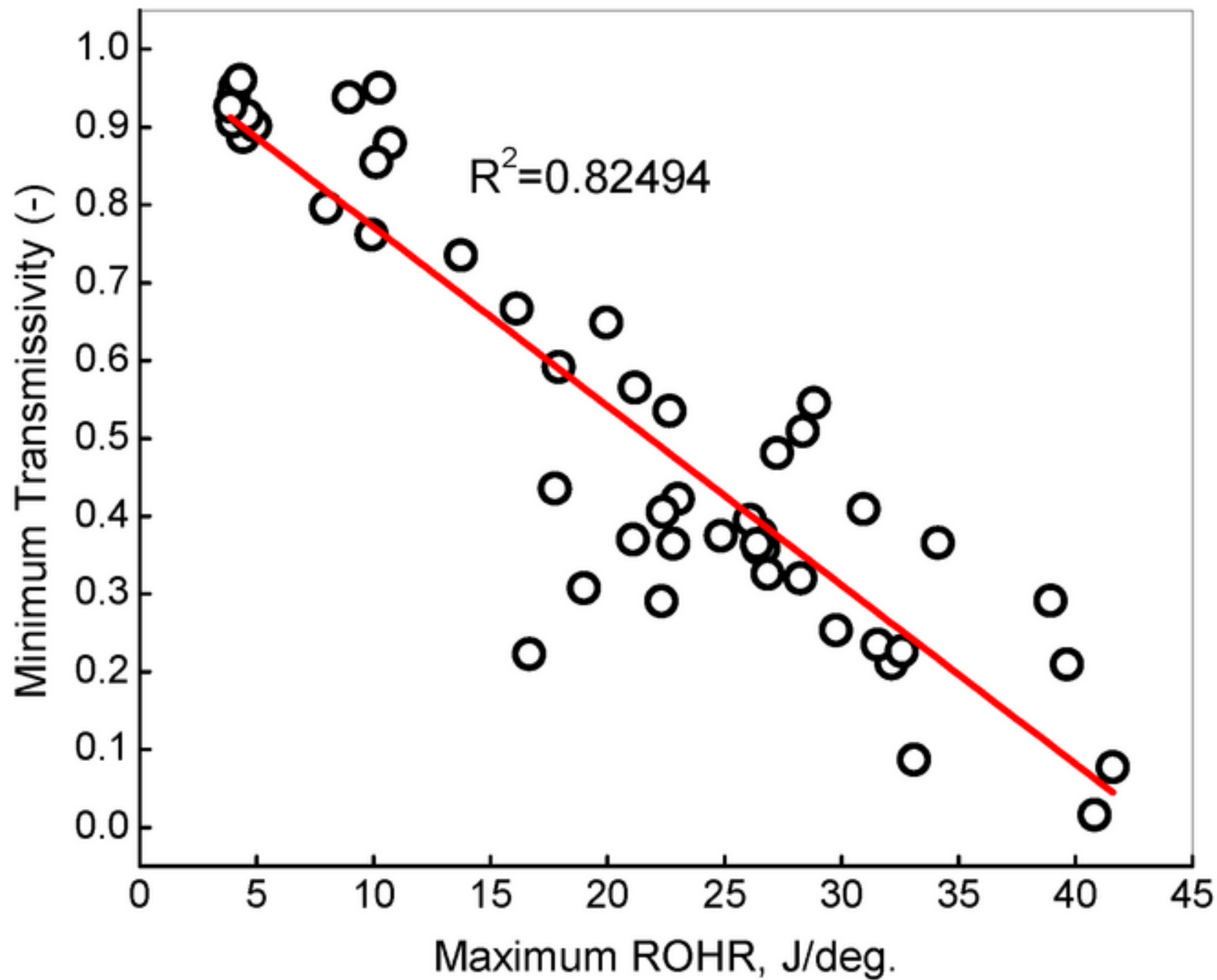


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