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CO_2 concentration measurements inside expansion-compression engine under high EGR conditions using an infrared absorption method

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ABSTRACT

The purpose of this study is to measure the high concentrations of CO_2 near a spark plug inside an internal combustion engine, and an infrared absorption method is used for the measurement. The spark plug sensor was adapted to a compression-expansion machine, and the CO_2 concentration near the spark plug was measured by adding a gas mixture, including CO_2 to imitate EGR. Next, the EGR ratio was changed from 10 to 40%, and the CO_2 concentration was measured. The effect of the CO_2 on the flame propagation was investigated by visualizing the bottom view of the compression-expansion machine. The measurements of CO_2 mass concentration are in agreement with those predicted by direct-absorption spectroscopy fundamental theory from the crank angle −60 to −15 deg ATDC. The error was less than 20%, and under the conditions with an EGR ratio of 20–40%.

1. Introduction

Determination of species concentrations inside a combustion chamber provides vital knowledge about the combustion process. The gas mixture in a combustion chamber consists of two main components: The fresh air-fuel mixture and the remaining burned gas from the previous cycle. The former component, i.e. the air-fuel mixture, determines the quality of combustion. It is quite important to adjust the air-fuel mixture prior to ignition to get reliable, clean, and safe operation of the combustion process. The undesirable emissions associated with combustion processes includes carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, and particulate matters. These emissions are facing increasingly stringent regulations. One of the most promising approaches to reduce pollution emissions is to dilute the air with recirculated gases from the previous ignition cycle. Exhaust gas recirculation (EGR) is a technology that is widely used to reduce and control nitrogen oxide (NO_x) emissions [1,2]. In EGR method a portion of engine exhaust gases returns to the combustion chamber via the intake system. As a consequence, the available amount of oxygen in the intake mixture for combustion will be reduced. The effective air-fuel ratio is lowered as a result of the oxygen reduction, which substantially affects the exhaust emissions. Mixing the intake air with exhaust gases will increase the specific heat of the intake mixture, resulting in a flame temperature reduction. A lower oxygen quantity in the intake air and a lower flame temperature reduces the NO_x formation reaction rate [3,4]. Higher fraction of EGR may reduce NO_x emission to 25% [5]. In addition to this desirable effect, EGR introduce cycle-to-cycle variations which substantially increase ignition delay times. [5–7]. For a multi-cylinder engine, the insufficient mixing of the EGR-air charge coupled with cycle-to-cycle variations may produce different charge gas composition, i.e. different ratio of the fresh air-fuel mixture and the exhaust gases, among the combustion chambers. This may introduce cylinder-to-cylinder variations [8]. EGR addition might also decelerate the burning velocity of the mixture which in turn may introduce prolongation of the burn duration, poor combustion phasing, higher optimum heat loss, and partial burning for the fuel-air mixture [9,10]. There are two types of EGR technique internal EGR and external EGR, according to the exhaust recirculation strategy. Internal EGR requires some mechanisms or variable valve timing (VVT) to retain a certain amount of exhaust gases from a previous

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cycle, where an external EGR can be conducted by producing a pressure difference between the inlet air and exhaust gases through an external pip arrangement [11]. Although EGR has become important control technology for advanced combustion [12] and alternate fuelled engine applications [13,14], improper use of EGR may lead to a reduction in engine durability and unstable operation[9].

In order to optimize and control this complicated process, high-speed diagnostic techniques are needed to determine the amount of gas recirculated in an engine during the intake and compression cycle, especially the gas near the spark plug. Currently, there are many methods to measure the residual gas concentration in a combustion chamber [15]. Recent advances in laser-based techniques have achieved the required interest in many cases and various instruments have become commercially available. Laser-based combustion diagnostics techniques have been developed and are of great interest because of their *in situ* measurement capability and nonintrusive nature. For instance, the Laser-Induced Fluorescence (LIF) [16] is very efficient for temperature and air-fuel ratios measurements because it is based on a spatially resolved measurements technique. However it needs sufficient optical access. It is also demanding in terms of the time needed for measurements. Additionally, special care should be taken for choosing the fluorescent tracer molecule, and sometimes it does not permit real-time measurements [17,18]. Rayleigh and Raman scattering techniques (SRS) [19], can measure the concentration of the molecule by measuring Raman scattering generated by shifting the incident light of a specific wavelength by the vibration energy of the molecule, and it is also possible to measure spatial distribution. However, Raman spectroscopy needs to be measured through a visualization window. Another problem is that molecules with high concentration and large Raman scattering cross section are targeted to a very weak scattered light. For that purpose, Yamamoto et al. mainly used measurements in stationary flow fields and measured the CO_2 concentration in a steady flow field using CARS (Coherent Anti-Stokes Raman Scattering) with stronger light intensity [20].

One of the well-established strategies of spectroscopic diagnostic for flow parameters measurements is the absorption [21,22]. Absorption measurements are particularly helpful in combustion diagnostics since they are extremely quick and selective, up to 40 kHz using spectroscopy with second-harmonic detection of wavelength modulation [23]. They can be used to quantify parameters such as concentration, and temperature without any disturbing of the flow of interest [24,25]. Absorption-based measurements can be employed in a variety of applications such as basic parameters studies of chemical-kinetic in shock tubes [26], and commercial sensors for emission control [27]. Measurements can be demonstrated using many sources that ranges from vacuum-ultraviolet (below 200 nm) to mid-infrared (mid-IR, up to 20 μm) sources. For combustion applications, the mid-IR spectrum is of great interest since many combustion products have distinct absorption features in this region [28]. Advanced optical diagnostic techniques [29] can be used to conduct high-sensitivity absorption measurements. With the continuous development of mid-IR light sources and detectors, measurements techniques based on mid-IR absorption are highly developed for many applications.

Carbon dioxide is considered one of the main exhaust gas constituents. It received high interest because it is usually used to estimate EGR ratio. CO_2 shows three discrete absorption bands in the mid-IR spectrum: Near 4.3 μm, 2.7 μm, and 2.0 μm. Each band is characterized by numerous individual absorption features, which correlate with different rovibrational transitions. Kawahara et al. [30] used infrared laser absorption to perform cycle-resolved residual gas concentration measurements inside a heavy-duty diesel engine [30]. They estimated the internal exhaust gas recirculation (EGR) ratio and quantified the CO2 concentration in the residual gas. I*n situ* measurements for *r*esidual gas concentrations, especially CO2 and H2O, have also been conducted using infrared absorption diagnostics [31,32]. Francqueville et al. [31] measured the CO2 concentration in the combustion chamber of a spark-ignited engine. Grosch et al. measured CO2 and gaseous H2O concentrations using infrared spectroscopy in environments that was difficult for direct measurement using a fiber optical sensor [33]. They used an optical absorption sensor to conduct quantitatively in-cylinder transmission measurements. They analyzed spectrally the CO2 and H2O mixture (wavelength: 3700 cm^{-1}, temperatures: 573 K, and pressures: 1800 kPa). In spark-ignited engines, the sensors used for mixture formation analyses are usually optical absorption-based sensors. These sensors have the advantage that enabled the access of the cylinder without any optical window. Consequently, measurements can be performed under realistic conditions and the engine's mechanical and thermodynamic properties under study will not be changed by the measurement tools. Optical absorption-based sensors combined with gas sampling probes can analyze the gas mixture inside the cylinder. In high-pressure combustion environments, little advancement has been achieved for the practical absorption-based sensors developments for CO2 measurements. Both the telecommunications diode lasers and the optical fiber, in the near-infrared (NIR) 1.3–1.6 μm wavelength) are used in many of the preceding high-pressure CO2 sensors. By direct absorption, these sensors can access weak vibrational bands of CO2 [34] by using direct absorption spectroscopy [35–37], wavelength modulation spectroscopy (WMS) [38,39], or NIR hyperspectral sources. A measurements of high-pressure CO2 absorption have been conducted near 2.0 μm, which explore the importance of optical sensor design for high-pressure applications [40].

In this study, the infrared absorption method was used for CO_2 concentration measurements near a spark plug at different EGR ratios. A distributed feedback (DFB) laser diode was used as the infrared light source with a wavelength near 4.2 μm. Propane was used as the base fuel, and pure gases were used to simulate EGR compositions to approximate the combustion of ideal products and propane ideal reformer products. The wavelength of 4195.7 nm was chosen for high concentration CO_2 measurements at different EGR ratios. Additionally, the effect of the CO_2 concentration on flame propagation was investigated by visualization.

2. Theory

Absorption is a selective process, which occurs as a result of light-matter interaction when photon energy is transferred to the molecule. Absorption is strongly dependent on molecular structure so the fundamental absorption line spectrum is unique for each gas species. For example, SO_2, NO_2, and NO all share the same characteristic absorption lines in the ultraviolet region. Many combustion-related species have rovibrational (rotational-vibrational) transitions in the mid-IR spectrum. Carbon dioxide gas (CO_2), our main focus in this study, has three fundamental absorption bands at three wavelengths, 4.3, 2.7 and 2 μm, as a result of the C—O vibrational rotational band. The fundamental band centred near 4.3 μm shows many strong absorption lines, and this band is generally well isolated from absorption interference when combustion products, including water and carbon dioxide, are present [41]. For accurate gas concentration measurements in practical internal combustion engines, a strong absorption coefficient is essential because of the limitation of the measurement length. The infrared absorption bands of CO_2 from 2 to 5 μm in wavelength at 300 K calculated by the HITRAN database [42] are shown in Fig. 1.

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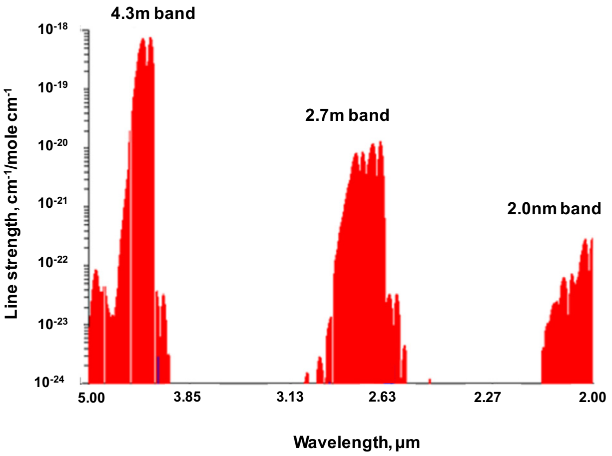

Fig. 1. Absorbance line strength of CO_2 at 300 K.

The direct-absorption spectroscopy fundamental theory has been explained in detail by many researchers [43,44] and it will be presented briefly to define our notation. When a beam of monochromatic light of intensity ***I*₀** enters a homogeneous absorbing gas of length ***l*,** the intensity of the transmitted light ***I*** will be

$$I = I_0 e^{-kl} \tag{1}$$

where ***k*** is a constant called the gas absorption coefficient.

This law was discovered by J.H. Lambert in 1790 [45]. A. V. Beer [46] found that in many cases, the concentration coefficient is proportional to the concentration of the absorbing gas.

$$k = C^{\varepsilon} \tag{2}$$

where ***C*** is the absorbing gas concentration and ***ℇ*** is the extinction coefficient of this gas.

The narrow-band laser absorption spectroscopy is governs by the basic physical relation stated in the Beer-Lambert law. It relates the intensity of light that enters an absorption medium I_0 to the transmitted intensity I as follows

$$\frac{I}{I_0} = e^{-\varepsilon Cl} \tag{3}$$

The term $\frac{I}{I_0}$ is known as the transmissivity.

3. Experimental methods

3.1. Residual gas in a compression expansion machine

Fig. 2 Shows the compression-expansion machine, which can be fired once. This machine is specially designed for this study. The engine has a bore of 78 mm, stroke of 67 mm and compression ratio of 6.7:1. The spark timing was at 345 degrees and an engine speed of 600 rpm. The cylinder has a quartz window 52 mm in diameter at the centre, making it possible for visualize from below. For visualization, a high-speed video camera MEMRECAM GX-8 manufactured by NACK image technology with a camera speed of 3 kfps was used.

In this study, the measurements were carried out at different EGR ratios. Propane was used as a base fuel and pure gases was used to simulate the EGR compositions to approximate both the ideal combustion and reformer products of Propane

According to the stoichiometric combustion of propane, the EGR compositions were chosen.

$$C_3H_8 + x[O_2 + 3.76N_2] \rightarrow yCO_2 + zH_2O + kN_2$$

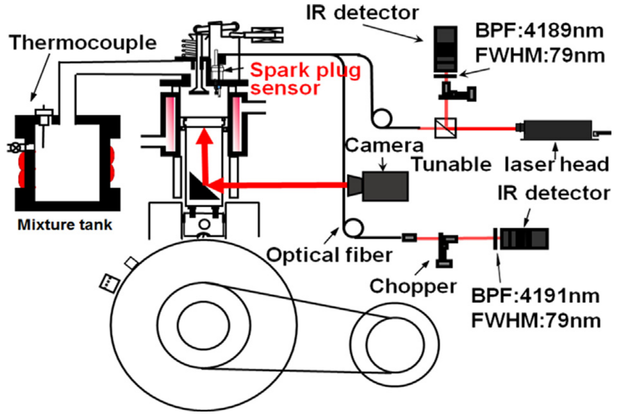

Fig. 2. Schematic of experiment set up with the compression- expansion machine.

We used 99% pure propane and dry compressed air The EGR is simulated by a mixture of A% CO_2 and B % N_2 depending on the desired ratio. All the percentages were composition by volume. Since the addition of water to the combustion chamber was not practical, a mixture of CO_2 and N_2 was used to simulate the combustion product.

The EGR (%) in this study is defined as:

$$EGR\% = \frac{m_{EGR}}{m_{air+fuel} + m_{EGR}} * 100$$

where $m_{air+fuel}$is the mass of fresh air and fuel, and m_{EGR} is the amount of exhaust gas that has the same volume of fresh air replaced. EGR ratio was changed from 10 to 40%.

A vacuum pump was used to evacuate the mixture tank and the chamber before each run. A pressure transducer was used to measure the pressure inside the combustion chamber. At every crank angle, the IR intensity signal in the cylinder pressure was recorded.

3.2. Optical sensor

An optical spark plug sensor (M14), which was modified from a commercial sensor [47,48] that allowed CO_2 concentration measurements near the spark plug under compression conditions, was used. Fig. 3 shows the construction of the modified optical sensor, which consists of three main optical parts: (1) two optical fibres, (2) a sapphire lens and (3) a metal mirror. Since the pressures and temperatures of the combustion gas are very high, the sapphire lens shield the fibres end faces from being damaged. The infrared light travelled from the laser source to the sensor using one of the optical fibres. The light passed through the sapphire lens and was then reflected by the mirror. The reflected light was transferred by the other optical fibre, passed through the sapphire lens again, and detected by a Hamamatsu Photonics

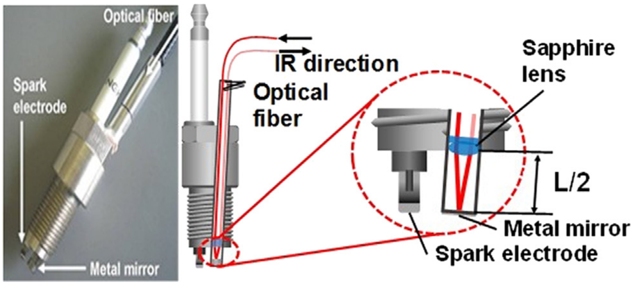

Fig. 3. Schematic diagram of spark plug sensor.

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P4631_04 detector. As shown in the figure, the gap between the sapphire lens and the mirror was the measurement region. The measurement length was twice this gap, and since the light passes the gap twice in both directions, the measurement length was 11 mm. In this study a newly developed optical spark plug sensor (M12) was also used. The optical components is the same for both sensors, but the assembling method and the hole inlet is different as shown in Fig. 4.

3.3. Laser device and wavelength selection

In this experiment, a distributed feedback laser diode (DFB-LD) was used as an infrared light source, and a Hamamatsu Photonics P4631_04 detector was used as the IR detector. The laser device is shown in Fig. 5. The device uses mid-infrared (mid-IR) source radiation, which is based on difference frequency generation (DFG) in a periodically poled lithium niobate (PPLN) crystal. An additional wavelength oscillator power amplifier source was incorporated for simultaneous amplification of 1064 nm and 1426.5 nm signals in a fibre. The wavelengths in the range of 4175–4200 nm can be irradiated. The laser wavelength range can access the mid-range of the fundamental vibrational band of CO_2 near 4.2 μm. The upper graph in Fig. 5 represents the CO_2 absorption features in the range from 4170 nm to 4210 nm measured at temperature 300 K and 5% of CO_2. Further, the lower graph shows the reflected laser intensity, and wavelengths of 4175, 4190, 4195, and 4200 nm were selected.

The laser intensity and wavelengths were varied by changing the diode laser temperature and operating current [49,50]. A wave metre with a resolution of approximately 0.3 nm was used for the wavelength measurements

Since the intensity of absorption depends on the wavelength, it is necessary to select the suitable wavelength for measuring the CO_2 concentration under the experimental conditions. First the effect of pressure on the CO_2 absorption line was examined using HITRAN. Fig. 6 shows that the intensity of the absorption line greatly depends on the pressure.

When EGR increases, the engine operation reaches zones with higher instabilities and increased carbonaceous emissions. For this reason, the best wavelengths selection for the measurements was validated at EGR ratio of 40%. Fig. 7 shows the results of comparing the measurement results of the transmissivity measured at EGR 40% and the transmittance calculated from HITRAN at different wavelengths. I_0 can be obtained by measuring the intensity of infrared light through the beam splitter before entering the fibre. The solid lines indicate the measured value, and the symbols indicate the calculated value from HITRAN. The transmittance value calculated using HITRAN was obtained by using the pressure and the concentration value of CO_2 contained in EGR 40% at five points of −180, −135, −90, −45, 0 deg ATDC. From the transmittance history, it was confirmed that the CO_2 molar concentration increased as compression progressed, and more absorption occurred. From these five wavelengths, the wavelength of 4195.7 nm was selected

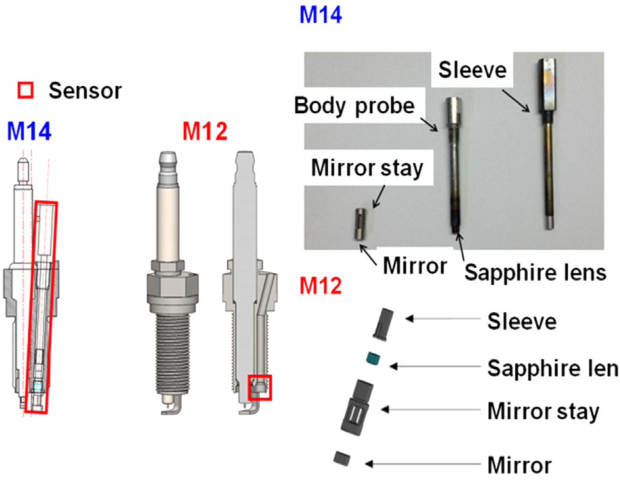

Fig. 4. Spark plug sensor M14 & M12.

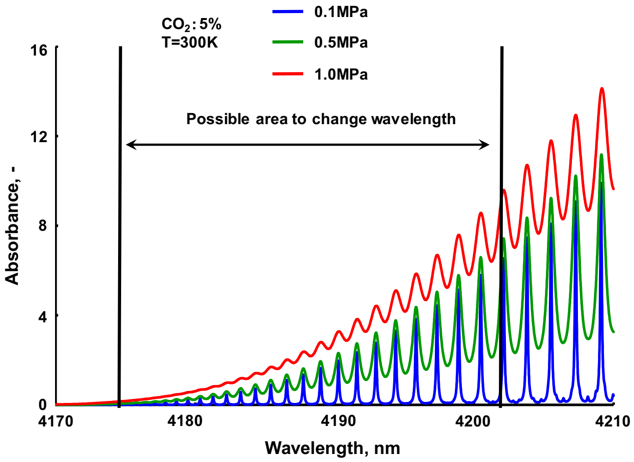

Fig. 6. Effect of pressure on CO_2 absorption line (4170–4210 nm).

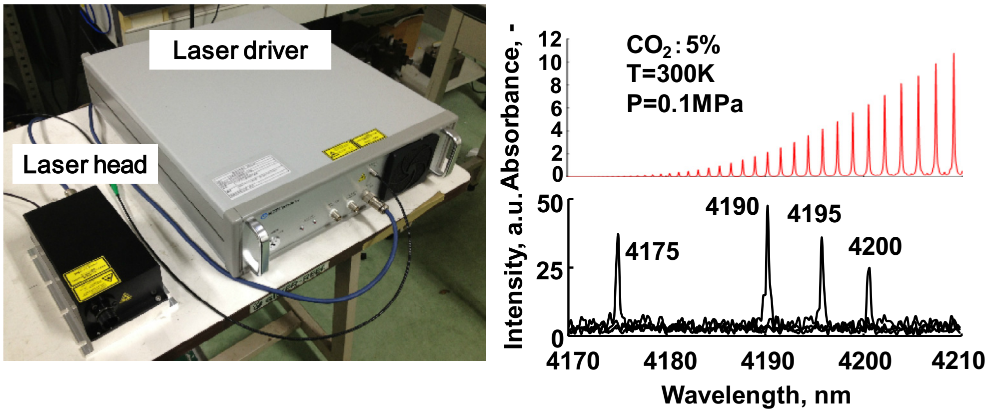

Fig. 5. Infrared light source and examples of the wavelength.

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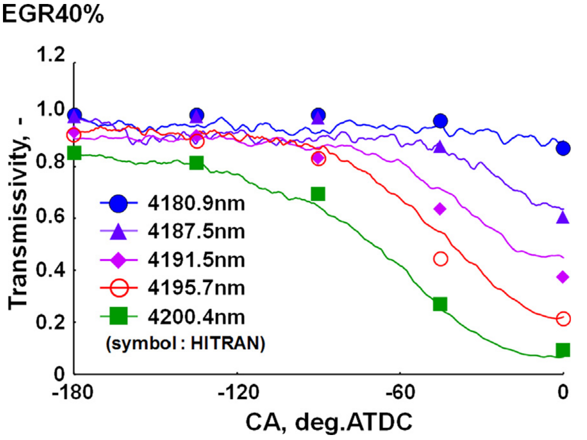

Fig. 7. Comparison between measured transmissivity and HITRAN at different wavelengths.

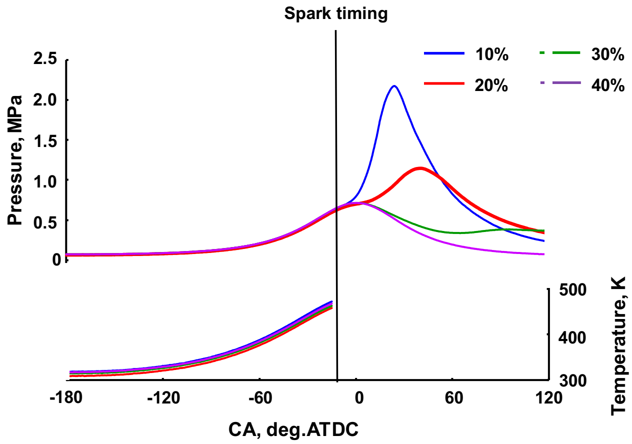

Fig. 9. Pressure and temperature history.

as the wavelength at which the absorption was too strong and the transmittance was not much less than 0.2, particularly in the vicinity of the compressed TDC. In addition, when examining the error of the calculated value from HITRAN, the error of 4200.4 nm at −45 deg for the ATDC is approximately 24%; for the errors of 4191.5 nm and 4200.4 nm at 0 deg, the ATDC increases to approximately 17% and 36%, respectively, although it was confirmed that the error was approximately 10% elsewhere.

Initially, The IR transmissivity was measured at wavelength 4195.7 nm using M12 and M14 optical sensor at EGR 10% and EGR 40% as shown in Fig. 8. The transmissivity data with M12 is the average value of 3 cycles, while that for M14 is the average value of 15 cycles. This may explain the fluctuation for the transmissivity measured using M14. The measurement was performed using M14 spark plug because of the limitation of accuracy of the initial light intensity measurement with the M12 spark plug.

Fig. 9 shows the pressure and temperature history, per crank angle degree at each EGR condition, the initial temperature inside the mixture tank was only measured, while the polytropic process equation is utilized to calculate the temperature during the compression. The pressure and temperature are changed inside the cylinder, especially in combustion and expansion stages. The pressure peak value was for lower EGR ratio (10%).

4. Results and discussion

The effect of the CO_2 influence on the flame propagation was investigated by visualizing from the bottom of the compression-expansion machine. A MEMRECAM GX-8 high speed camera with a speed of 3 kfps manufactured by NACK Image Technology was used. Fig. 10 shows the flame propagation change every 6 deg from −15 deg ATDC, which is the spark timing. It can be shown that the flam spread very quickly, which caused the combustion to finish quickly. For EGR 30%, the pressure showed a slight change, which resulted in the combustion slightly burning. Almost no combustion occurred at 40% EGR. At higher EGR, a reduction in the flame temperature as a result of the spatial broadening of the flame is caused as a result of displacement of oxygen by inert gases. This reduction of the peak combustion temperature slows down the combustion speed. Also heat capacity is changed, since the specific heat capacity of the exhaust gas is higher than that of air. So a mass of gas containing EGR will have a lower temperature than pure air for the combustion energy same amount.

Next, the measurement results for the pressure and temperature history from −180 to 0 deg ATDC and the transmittance under each EGR condition are shown in Fig. 11. The results of the transmittance shown in Fig. 11 show the average value for three cycles.

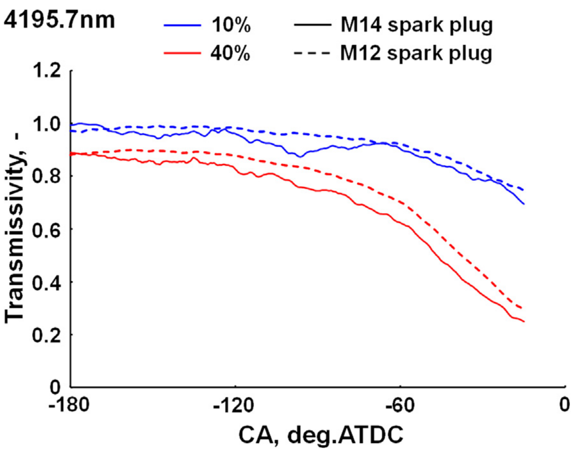

Fig. 8. Comparison of transmissivity with M12 & M14 using 4195.7 nm.

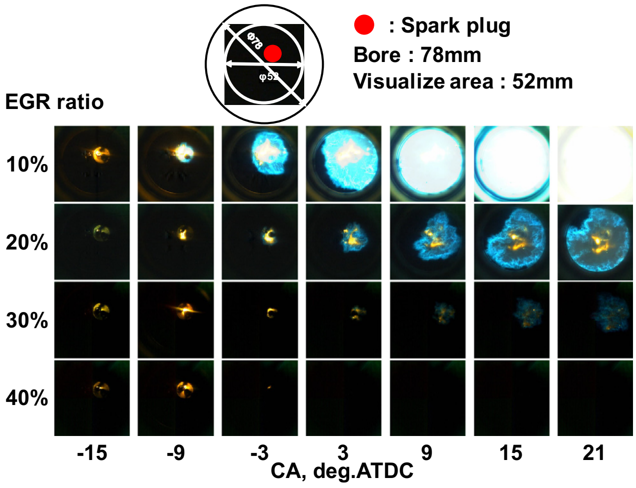

Fig. 10. Visualization of combustion in each EGR ratio.

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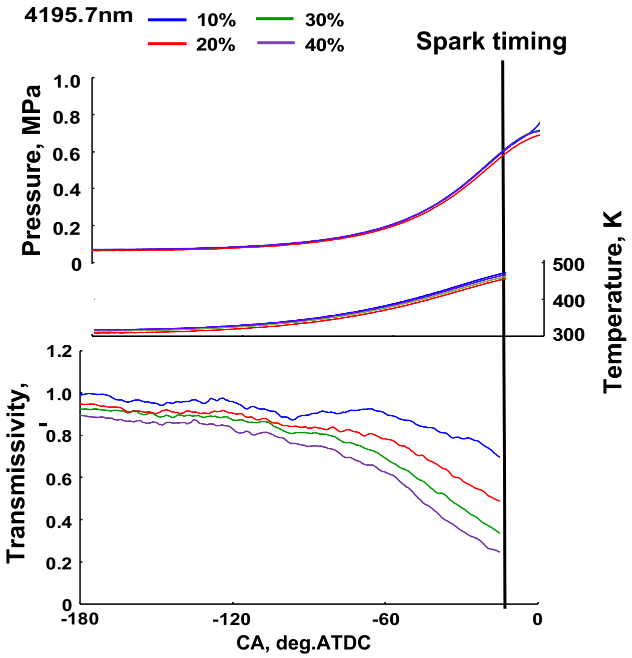

Fig. 11. Pressure, temperature and transmissivity history.

The result of the CO_2 concentration calculated from the transmittance result is shown in Fig. 12. The broken line is a value obtained by previously calculating the concentration of CO_2 contained in the premixed gas, and the solid line shows the measurement result. The maximum deviation between the calculated and measured values between −90 and 0 deg ATDC was approximately 54% at EGR 10%, 28% at EGR 20%, 10% at EGR 30% and 10% at EGR 40%. However, when looking at the maximum deviation between −60 and 15 deg, the ATDC was approximately 18% for EGR 10%, 8% for EGR 20%, 6% for EGR 30% and 10% for EGR 40%. For the overall EGR results, the deviation was less than 20%, and the maximum deviation under the condition of an EGR rate from 20 to 40% was less than approximately 10%. The deviation between the measured and the present values may be attributed to the small change in pressure and the large volume in the vicinity of −90 deg ATDC so that the molar concentration is small. The engine vibration which may also affect the light transmitted from the optical fibres. Also the measurement error resulting from noise and repeatability for any laser-based measurement system play a role in the deviation.

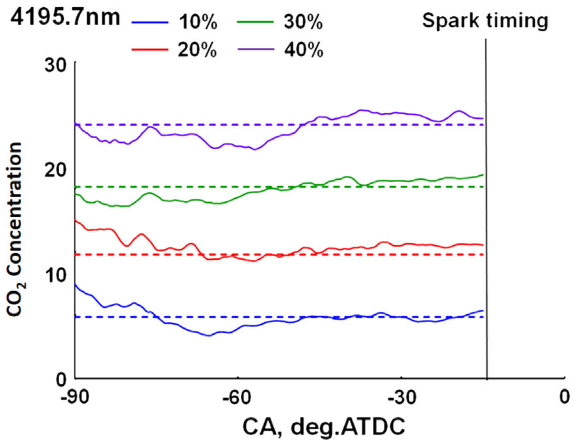

Fig. 12. Comparison of CO_2 mass from the transmittance results and that contained in the premixed gas.

5. Conclusion

In a compression-expansion engine, a premixed gas was prepared, and the CO_2 concentration near the spark plug was measured by the IR absorption method at different EGR ratios. A distributed feedback laser diode (DFB-LD) was used as the infrared light source with a wavelength near 4.2 μm, which is the fundamental vibrational band of CO_2. Propane was used as the base fuel, and pure gases were used to simulate the EGR compositions to approximate both the ideal combustion and propane reformer products. The wavelength at 4195.7 nm was chosen for high CO_2 concentration measurements at different EGR ratios. As a result, the following knowledge was obtained:

1. CO_2 concentration measurements near the spark plug can be performed at different EGR ratios by the IR absorption method.
2. When quantitatively measuring the CO_2 concentration in the vicinity of the spark plug, the maximum deviation between the measured and the present values was approximately 20% for the overall EGR ratio conditions.

References

[1] Palash SM, Masjuki HH, Kalam MA, Masum BM, Sanjid A, Abedin MJ. State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled Compression Ignition engines. Energy Convers Manage 2013;76:400–20.
[2] Bermúdez V, Lujan JM, Pla B, Linares WG. Effects of low pressure exhaust gas recirculation on regulated and unregulated gaseous emissions during NEDC in a light-duty diesel engine. Energy 2011;36(9):5655–65.
[3] Ladommatos N, Balian R, Horrocks R, Cooper L. The effect of exhaust gas recirculation on soot formation in a high-speed direct-injection diesel engine. SAE Technical Paper 1996.
[4] Abd-Alla GH. Using exhaust gas recirculation in internal combustion engines: a review. Energy Convers Manage 2002;43(8):1027–42.
[5] Zheng M, Reader GT. An experimental analysis of EGR on operational stabilities of Diesel engines. ASME ICE 2001;36:1.
[6] Zheng M, Reader GT. Preliminary investigation of cycle-to-cycle variations in a nonair-breathing diesel engine. J Energy Resour Technol 1995;117(1):24–8.
[7] Zheng M, Reader GT, Galinsky G, Potter LJ, Gustafson RW. Ignition delay and pressure-time characteristics in a diesel engine using carbon dioxide and argon enriched oxidants. In: Energy-sources technology conference and exhibition, Houston, TX, USA, 01/31-02/04/93. p. 1–7.
[8] Hansel JG. Lean automotive engine operation—Hydrocarbon exhaust emissions and combustion characteristics. SAE Trans 1971:708–22.
[9] Heywood JB. Internal combustion engine fundamentals; 1988.
[10] Wyszyńska ML et al. Improved combustion in high EGR dilution CNG engines and fuel reforming with exhaust gas. Arch Combust 2000;20(3–4):19–29.
[11] Thangaraja J, Kannan C. Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels-A review. Appl Energy 2016;180:169–84.
[12] Asad U, Zheng M. Exhaust gas recirculation for advanced diesel combustion cycles. Appl Energy 2014;123:242–52.
[13] Selim MYE. Effect of exhaust gas recirculation on some combustion characteristics of dual fuel engine. Energy Convers Manage 2003;44(5):707–21.
[14] Daisho Y, Yaeo T, Koseki T, Saito T, Kihara R, Quiros EN. Combustion and exhaust emissions in a direct-injection diesel engine dual-fueled with natural gas. SAE Technical Paper 1995.
[15] Zhao H, Ladommatos N. Engine combustion instrumentation and diagnostics. Engine Combust Instrum Diagnostics 2011.
[16] Kohse-Höinghaus K. Laser techniques for the quantitative detection of reactive intermediates in combustion systems. Prog Energy Combust Sci 1994;20(3):203–79.
[17] Luong M, Zhang R, Schulz C, Sick V. Toluene laser-induced fluorescence for in-cylinder temperature imaging in internal combustion engines. Appl Phys B 2008;91(3–4):669.
[18] Schulz C, Sick V. Tracer-LIF diagnostics: quantitative measurement of fuel concentration, temperature and fuel/air ratio in practical combustion systems. Prog Energy Combust Sci 2005;31(1):75–121.
[19] Laurendeau NM. Temperature measurements by light-scattering methods. Prog Energy Combust Sci 1988;14(2):147–70.
[20] Yamamoto K, Yamagata Y, Moriya M, Kuriyama R, Sato Y. A non-intrusive measurement technique applying CARS for concentration measurement in a gas mixing flow. arXiv Prepr 2015.
[21] Furlong ER, Baer DS, Hanson RK. Combustion control using a multiplexed diode-laser sensor system. Symp (Int) Combust 1996;26(2):2851–8.
[22] Allen MG. Diode laser absorption sensors for gas-dynamic and combustion flows. Meas. Sci. Technol. 1998;9(4):545.

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[23] Farooq A, Jeffries JB, Hanson RK. Sensitive detection of temperature behind reflected shock waves using wavelength modulation spectroscopy of CO 2 near 2.7 μm. Appl Phys B 2009;96(1):161–73.

[24] Bowman CT, Hanson RK. Shock tube measurements of rate coefficients of elementary gas reactions. J Phys Chem 1979;83(6):757–63.

[25] Hanson RK, Falcone PK. Temperature measurement technique for high-temperature gases using a tunable diode laser. Appl Opt 1978;17 (16):2477–80.

[26] Farooq A, Jeffries JB, Hanson RK. CO 2 concentration and temperature sensor for combustion gases using diode-laser absorption near 2.7 μm. Appl Phys B 2008;90(3–4):619–28.

[27] Martin PA. Near-infrared diode laser spectroscopy in chemical process and environmental air monitoring. Chem Soc Rev 2002;31(4):201–10.

[28] Jeffries JB, Kohse-Hoinghaus K. Applied combustion diagnostics. Taylor & Francis; 2002.

[29] Silver JA. Frequency-modulation spectroscopy for trace species detection: theory and comparison among experimental methods. Appl Opt 1992;31 (6):707–17.

[30] Kawahara N, Tomita E, Ohtsuki A, Aoyagi Y. Cycle-resolved residual gas concentration measurement inside a heavy-duty diesel engine using infrared laser absorption. Proc Combust Inst 2011;33(2):2903–10.

[31] de Francqueville L, Thirouard B, Ricordeau V. Measurement of residual gas fraction using IR absorption. SAE Technical Paper 2006.

[32] Hall MJ, Zuzek P, Anderson RW. Fiber optic sensor for crank angle resolved measurements of burned gas residual fraction in the cylinder of an SI engine. SAE Trans 2001:1763–70.

[33] Grosch A, Wackerbarth H, Thiele O, Berg T, Beckmann L. Infrared spectroscopic concentration measurements of carbon dioxide and gaseous water in harsh environments with a fiber optical sensor by using the HITEMP database. J Quant Spectrosc Radiat Transf 2014;133:106–16.

[34] Kranendonk LA, Walewski JW, Kim T, Sanders ST. Wavelength-agile sensor applied for HCCI engine measurements. Proc Combust Inst 2005;30 (1):1619–27.

[35] Schlosser E, Fernholz T, Teichert H, Ebert V. In situ detection of potassium atoms in high-temperature coal-combustion systems using near-infrared-diode lasers. Spectrochim Acta Part A Mol Biomol Spectrosc 2002;58 (11):2347–59.

[36] Mattison DW et al. In-cylinder gas temperature and water concentration measurements in HCCI engines using a multiplexed-wavelength diode-laser system: sensor development and initial demonstration. Proc Combust Inst 2007;31(1):791–8.

[37] Sanders ST, Baldwin JA, Jenkins TP, Baer DS, Hanson RK. Diode-laser sensor for monitoring multiple combustion parameters in pulse detonation engines. Proc Combust Inst 2000;28(1):587–94.

[38] Rieker GB et al. Rapid measurements of temperature and H2O concentration in IC engines with a spark plug-mounted diode laser sensor. Proc Combust Inst 2007;31(2):3041–9.

[39] Fernholz T, Teichert H, Ebert V. Digital, phase-sensitive detection for in situ diode-laser spectroscopy under rapidly changing transmission conditions. Appl Phys B 2002;75(2–3):229–36.

[40] Rieker GB, Jeffries JB, Hanson RK. Measurements of high-pressure CO 2 absorption near 2.0 μm andá implications on tunable diode laser sensor design. Appl Phys B 2009;94(1):51–63.

[41] Kawahara N, Tomita E, Tanaka Y. Residual gas fraction measurement inside engine cylinder using infrared absorption method with spark-plug sensor. SAE Technical Paper 2007.

[42] Rothmana ABLS, Jacquemarta D, et al. The HITRAN 2004 molecular spectroscopic database. J Quant Spectrosc Radiat Transf 2004;96:139–204.

[43] Nagali V, Chou SI, Baer DS, Hanson RK, Segall J. Tunable diode-laser absorption measurements of methane at elevated temperatures. Appl Opt 1996;35 (21):4026–32.

[44] Baer DS, Nagali V, Furlong ER, Hanson RK, Newfield ME. Scanned-and fixed-wavelength absorption diagnostics for combustion measurements using multiplexed diode lasers. AIAA J 1996;34(3):489–93.

[45] Swinehart DF. The beer-lambert law. J Chem Educ 1962;39(7):333.

[46] Beer A. Determination of the absorption of red light in colored liquids. Ann Phys Chem 1852;86:78–88.

[47] Kawahara N, Tomita E, Nishiyama A, Hayashi K. In-situ fuel concentration measurement near spark plug by 3.392 mm infrared absorption method—pressure and temperature dependence of the gasoline molar absorption coefficient. SAE Technical Paper 2006.

[48] Kawahara N, Tomita E, Hayashi K, Tabata M, Iwai K, Kagawa R. Cycle-resolved measurements of the fuel concentration near a spark plug in a rotary engine using an in situ laser absorption method. Proc Combust Inst 2007;31 (2):3033–40.

[49] Yulianto N, Widiyatmoko B, Priambodo PS. Temperature effect towards DFB laser wavelength on microwave generation based on two optical wave mixing. Int J Optoelectron Eng 2015;5(2):21–7.

[50] Singal TL. Optical fiber communications: principles and applications. Cambridge, U.K.: Cambridge Univ. Press; 2017.

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