Power and Energy Characteristics of Continuous Waves / Pulsed CO₂ Laser Application in CNG-DI Ignition

N. Mariun, N. Md. Saad, M. F. Abas, N. Khan and S. Abdullah

Abstract—This work was arranged to develop the scientific database and integrate the application of lasers in high voltage engineering. The design and experimental studies on continuous wave (CW) / repetitively pulsed CO₂ laser was carried out in detail to determine the laser characteristics between various design parameters and the effect of varying one parameters on others. The thresholds and steady state input voltage and power across the laser tube are determined. The maximum and minimum output energy and power of the laser system are also presented as function of the pulse repetition rate and discharge current. The CO₂ laser system was operated at 10.6 µm wavelengths range of infrared electromagnetic spectrum. This study is presented due to the wide applications of CO₂ lasers in industry and for this project for compressed natural gas: direct injection (CNG-DI) ignition.

Keywords—CO₂ laser, continuous wave, repetitively pulsed wave.

I. INTRODUCTION

This paper presents an explanation of the lasing processes involved for continuous wave and repetitively pulsed CO₂ laser at 10.6µm in terms of laser energy and power characteristics. The CO₂ molecule is symmetric and it consists of two oxygen atom tied to a central carbon atom by elastic forces. These molecules can vibrate and rotate at their equilibrium position. The total energy of the molecules is due to the contributions of both vibrational and rotational motions. These motions are characterized by corresponding quantum numbers [1].

The purpose of this project is to build a CO₂ laser system for application in CNG-DI ignition.

II. LASER ENERGY AND POWER

If the power distribution of the laser beam is assumed Gaussian, as shown in Fig.2, then the laser pulse energy for appropriate pulse duration is calculated below [7]-[11],

\[ E(\tau) = E_{max} \exp(-\tau^2 / \tau^2) \] (1)

Where E is the pulse energy (J), Emax is the maximum laser energy, \( \tau \) is the time, and \( t_o \) is the time at which \( E(t_o) = E_{max}/e \), (e = 2.7183).

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N. Mariun, is with the Department of Electrical & Electronics Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia. (phone: 60389466266; Fax: 6038657103; e-mail: norman@eng.upm.edu.my).

N. Md. Saad, was with Department of Electrical & Electronics Engineering, Universiti Putra Malaysia, Serdang, Malaysia. She is now with Faculty of Electrical & Electronics, Universiti Malaysia Pahang, Lock Bag 12, 25000 Kuantan, Pahang, Malaysia. (e-mail: norhafidzah@ump.edu.my).

M. F. Abas, was with Department of Electrical & Electronics Engineering, Universiti Putra Malaysia, Serdang, Malaysia. He is now with Faculty of Electrical & Electronics, Universiti Malaysia Pahang, Lock Bag 12, 25000 Kuantan, Pahang, Malaysia. (e-mail: mfdhil@ump.edu.my).

N. Khan was with Department of Electrical & Electronics Engineering, Universiti Putra Malaysia, Serdang, Malaysia.

S. Abdullah is with the Faculty of Engineering, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.
Let \( \tau_{\text{FWHM}} \) be the pulse duration (full width at half maximum). Then \( \tau_0 \) is calculated from the following relation,

\[
\tau_0 = \frac{\tau_{\text{FWHM}}}{2\sqrt{\ln 2}}
\]  

(2)

The average laser energy, \( E_0 \) over \( \tau_0 \) is given as,

\[
E_0 = \int_{-\infty}^{\infty} P(t) dt
\]

(3)

From Figure 2,

\[
P(t) = P_{\text{max}} \exp \left( -\frac{\tau^2}{\tau_0^2} \right)
\]

(4)

Where \( P_{\text{max}} \) is the maximum laser power (Watts). Using (4) into (3) gives,

\[
E_0 = \int_{-\infty}^{\infty} P_{\text{max}} \exp \left( -\frac{\tau^2}{\tau_0^2} \right) dt
\]

(5)

Maximum power, \( P_{\text{max}} \) relates to initial laser energy, \( E_0 \) by the following relation,

\[
P_{\text{max}} = \frac{E_0}{\tau_0 \sqrt{\pi}}
\]

(6)

III. DESIGN AND EXPERIMENTAL PROCEDURES

The CO\(_2\) laser system which is used in this work is shown in Fig.3. A 20 kV power supply was used to excite the laser tube. The mirrors constituting a resonator are attached to the laser tube windows after alignment. Four fans are used for cooling of the laser system.

The laser system control unit is designed to control the CO\(_2\) laser operation. The CO\(_2\) laser was operated in continuous wave (cw) mode and in repetitively pulsed mode.

The experimental setup consists of CO\(_2\) laser system with the control unit, R-752 Universal Laser Radiometer unit (DigiRad Division of TeraHertz Tech. Inc.) and the digital oscilloscope (Textronix). The R-752 Universal Laser Radiometer unit consists of P-444 pyroelectric energy meter probe and PH-30 power head in order to obtain the profile of the energy in a short pulse of light and power of a continuous wave of light for comparison with the output profile from the oscilloscope. The schematic diagram of the studies can be seen in Fig.4 below.

The measurements were obtained by varying the discharge current, pulse repetition rate (PRR), pulse repetition time (PRT), pulse duration and duty cycle of the laser system. These can be simply done through the control unit which has been designed for driving the CO\(_2\) laser system in order to get
the output profiles in continuous waves or in pulsed mode.

**IV. RESULTS AND DISCUSSION**

The results and discussions are presented in detail for the measurement of threshold and steady state voltage across the laser tube and the output energy and power of the laser system. These works were carried out subject to pulse repetition rate and the discharge current of the laser system.

**A. Thresholds and Steady State Voltage**

The measurements of the thresholds and steady state voltage across the laser tube were done when the laser system is operated in continuous wave (cw) mode. The threshold and steady state voltage across the laser tube was measured to be 15.64 kV and 8.16 kV, respectively. The thresholds voltage electric discharge starts between the electrodes through the gas mixture. As the discharge starts, the threshold voltage drops to steady state voltage. The steady state voltage remains unchanged as discharge current increased as shown in Fig.5. However, the input power increased linearly as the discharge current increased as shown in Fig.6.

**B. Output Energy**

The output pulse energy has been measured experimentally as function of pulse repetition rate and discharge current. The energy measurements are performed using P-444 Pyroelectric energy meter probe which placed in front of the laser beam. The power supply to P-444 was switched on. The meter will automatically scale to pulse energy measurement and will display the reading in joule on the LCD display. The energy meter is averaged to 100 samples. The pulse repetition rate was increased in steps starting from 25 Hz up to 1500 Hz at fix discharge current and the energy of the pulse is calculated. The processes were then repeated for different values of discharge current.

The pulse energy is found to increase with the increase in pulse repetition rate. The maximum pulse energy was found at 50 Hz at the discharge current of 10mA which is about 32mJ. A decrease in the pulse energy was noted with further increase in pulse repetition rate. This is due to the decrease in the on time of the input electric discharge through the lasing media which will cause the probability of all the molecules in the upper level decreases.

For the measurement of the energy as function of discharge current, the discharge current was increased in steps up to 20mA at fix pulse repetition rate. Then, the processes were repeated for different values of pulse repetition rate and the energy of the pulse is calculated. Again, it yielded the same results in which the maximum output energy was found at 32mJ with 50 Hz pulse repetition rate and 10mA discharge current. The results were illustrated in Fig.7 and Fig.8 respectively.
C. Output Power

For the measurements of the output power, the laser system was operated in both, continuous wave and pulsed mode. The output power measurements were performed using P-444 Pyroelectric energy meter with PH-30 power head which is placed in front of the laser beam. The meter will automatically scale to power measurement and display the reading in watts on the LCD display.

The results for measurements of output power in pulsed mode as function of pulse repetition rate at different discharge current can be seen in Fig.9.

An increase in maximum power has been found with increase in pulse repetition rate. The highest output power is achieved at 10mA discharge current with the pulse repetition rate of 400 Hz, which is 11.02 watts. The further increase in pulse repetition rate and discharge currents results in decrease of maximum power. This is due to the increase in the energy which will increase the rate of collision between the molecules and electrons. The increase in the rate of collision causes the population density of the lower levels to increase, which hinder the transition from upper level to lower level. This blocking in the transition path causes the reduction in output power of the laser system. In the continuous wave operation, the output power is maximum when the population density of upper levels becomes equal the population density of lower levels in the ground state.

The results for measurements of output power in continuous wave as function of discharge current can be seen in Fig.10. It was found that the laser power increases with increase in the current. This increase in power continues until the discharge current reaches to a value of 14mA. The further increase in currents results in decrease of output power. The maximum power was found at 12.12 watts at 14mA discharge current. The relationship between the output power and discharge current is given by [2],

\[ P = -0.065I^2 + 1.796I + 0.294 \]  

(7)
and the average power is given by,

\[
P_{\text{avg}} = \frac{E}{PRT} = E \times PRR
\]  

(8)

Again, the average power continues increase until it reaches a maximum value and then starts decreasing with further increase in discharge current and pulse repetition rate. The highest power average is achieved at 10mA of discharge current with pulse repetition rate of 400Hz, which is about 4.7 watts. The further increase in pulse repetition rate results in the decrease of output power average.

The calculation for maximum power was done to compare the theoretical and experimental results of CO2 laser in term of maximum power characteristics. The results were tabulated in Fig.12. The results of experimental findings are acceptable with percentage of total power loss less than 10%. Equation (9) gives the total power loss for experimental finding as function of discharge current [1].

\[
P_{\text{loss}} = (-0.0657I^2 + 1.796I + 0.294)
\]  

(9)

\[
D. \ \text{Application in CNG-DI Ignition}
\]

The absorption characteristics of leaner air/ compressed natural gases (CNG) mixtures have been experimentally investigated using continuous wave (cw)/pulsed CO2 laser at 10.6µm at variable laser energy and pressures operated at 295K temperature. The measurements were done using optical transmission loss techniques with 19% transmission loss due to optical window and lens.

The purpose of this experiment is to investigate the application of continuous wave (cw)/repetitively pulsed CO2 laser system for compressed natural gases-direct injection (CNG-DI) laser ignition system.

The results for absorption coefficients, \( k_v \) are shown in Fig.13 and Fig.14 respectively. As \( E_0 \) or pressure increased, the absorption coefficient, \( k_v \) of CO2 laser in CNG, air and CNG/air mixtures increased drastically in the region of \( E_0 \) less than 25mJ or pressure less than about 2 to 3 bar. Depending on \( E_0 \) or pressures, the absorption coefficients are in the range from \( 2\text{cm}^{-1} \) to about \( 51\text{cm}^{-1} \) for CNG, \( 0.85\text{cm}^{-1} \) to \( 48\text{cm}^{-1} \) for air and \( 1\text{cm}^{-1} \) to \( 50\text{cm}^{-1} \) for CNG/air mixtures. The curves for absorption coefficient, \( k_v \) of all the test gases were found in agreement with the exponential law of absorption that is call as Beer-Lambert Law.
V. CONCLUSIONS

The CO₂ laser system was successfully operated in continuous wave mode as well as in pulse mode to experimentally study the power and energy characteristics of CO₂ laser system at 10.6 μm. The variation in power and energy parameters of CO₂ laser have been analyzed experimentally as function of pulse time period and discharge current. The results of experimental findings were found acceptable with low power loss. These losses might be due to the rise of laser tube temperature which will cause output power to drop. Overall, the operation of CO₂ laser system in both, continuous wave and pulse mode was found stable optically and thermodynamically.

The study has shown that absorption coefficient significantly varies with change in pressures and the ratio of fuel/air mixtures over a wide range of laser energy. Absorption data showed a strong dependence on both laser energy and pressure. Laser wavelength has a strong effect on the absorption coefficient as function of total laser energy. The results were found to follow the exponential law of absorption that is called as Beer-Lambert Law.

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