Power and Energy Characteristics of Continuous Waves / Pulsed CO$_2$ Laser Application in CNG-DI Ignition

N. MARIUN[1], N. MD. SAAD[1], M.F. ABAS[1], N. KHAN[1], S. ABDULLAH[2]

Faculty of Engineering[1]
Universiti Putra Malaysia
Serdang, 43400
Malaysia

Faculty of Engineering[2]
Universiti Kebangsaan Malaysia
Bangi, 43600
Malaysia

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 CO$_2$ 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 CO$_2$ laser system was operated at 10.6 μm wavelengths range of infrared electromagnetic spectrum. This study is presented due to the wide applications of CO$_2$ lasers in industry and for this project for CNG-DI ignition.

Key-Words:- CO$_2$ Laser, Continuous wave, Repetitively pulsed wave.

1 Introduction

This paper presents an explanation of the lasing processes involved for continuous wave and repetitively pulsed CO$_2$ laser at 10.6μm in terms of laser energy and power characteristics. The CO$_2$ 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.

Three types of non-degenerate modes of vibration are symmetric stretching, bending and asymmetric stretching [1]. The most commonly observed laser transitions in the CO$_2$ molecule are from the CO$_2$ asymmetric stretch mode 001 to the symmetric stretch mode 100 (10.6μm) and to bending mode 020 (9.6 μm). The energy states of all of these vibrations are quantized and are represented by three quantum numbers, v_1, v_2, v_3 where v_1 refers to the symmetric stretch quantum number, v_2 refers to the bending quantum number and v_3 refers to the asymmetric stretch quantum number [2-4]. The energy levels diagram of CO$_2$ molecules involved in the lasing process are illustrated in Fig.1 [3-5].

Depends on the output power, CO$_2$ lasers have wide applications such as in communication, national defense and as tools in many area of scientific research. The high power of CO$_2$ lasers are widely used in industry for various purposes such as laser marking, laser cutting, welding, drilling and material processing. In medical instruments, CO$_2$ lasers are used for laser surgery, laser therapy, reduction of bleeding and neurosurgery [5]. In the area of scientific research, the CO$_2$ lasers at 10.6 μm are the most suitable for earth atmosphere ionization experiment and high voltage laser triggered lightning discharge [6]. Besides that, the most important research area to be explored is the infrared laser spectroscopy study in combustion research.

The purpose of this project is to build a CO$_2$ laser system which will be used for high voltage laser triggered discharge experiment and for application in CNG-DI ignition.

All works were performed at the High Voltage Laboratory in Electrical Engineering Department, Universiti Putra Malaysia (UPM), Serdang.

2 Laser Energy and Power

If the power distribution of the laser beam is assumed Gaussian, as shown in Fig.2, then the energy of the laser pulse for appropriate pulse duration is calculated by using the equation below [7-10],

$$E(\tau) = E_{max} \exp(-\tau^2 / \tau_\circ^2) \qquad (1)$$

Where E is the pulse energy (J), E_{max} is the maximum laser energy, τ is the time, and τ_o is the time at which $E(\tau_o) = E_{max}/e$, ($e = 2.7183$).
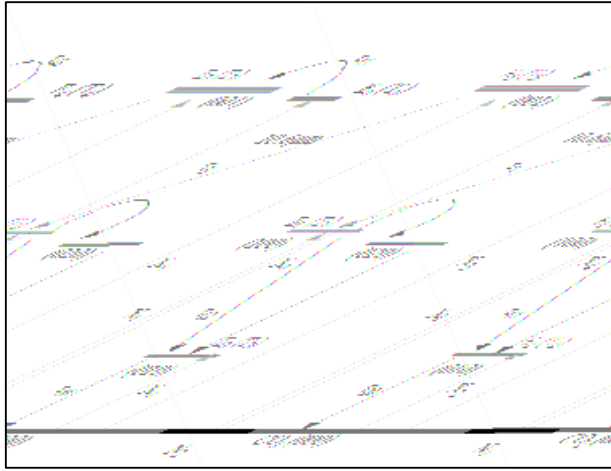
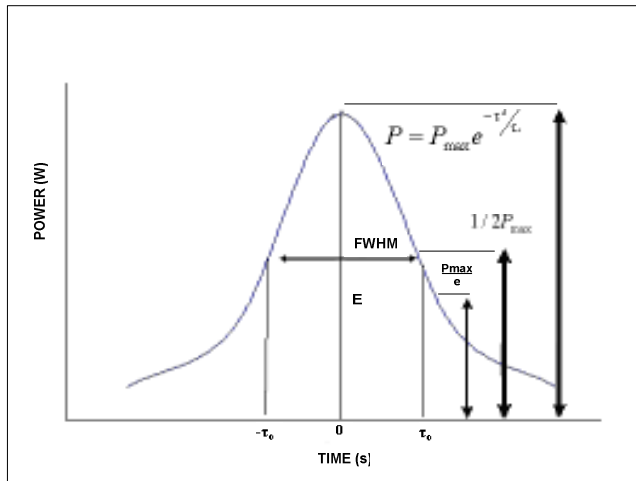Fig.1 Energy Level Diagram of Lasing Mechanism in CO_2 Laser [5-7]

Fig.2 Gaussian distribution of Laser Power from a Single Pulse [10]

Let τ_{FWHM} is the pulse duration (FWHM). Then τ_o is calculated from the following relation,

$$\tau_{\circ} = \frac{\tau_{FWHM}}{2\sqrt{\ln 2}} \qquad (2)$$

The average laser energy, $E_{\circ}$ over τ_o is given as,

$$E_{\circ} = \int_{-\infty}^{\infty} P(t)dt \qquad (3)$$

From Figure 2,

$$P(t) = P_{max} \exp\left(-\tau^2 \Big/ \tau_o^2\right) \qquad (4)$$

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

$$E_{\circ} = \int_{-\infty}^{\infty} P_{max} \exp(-\tau^2 \Big/ \tau_{\circ}^2)dt \qquad (5)$$

The average laser energy is also given as,

$$E_{\circ} = \frac{1}{\tau_{\circ}} \int_{-\infty}^{\infty} E(\tau)dt \qquad (6)$$

In equation (2) to (6), $\tau_{\circ}$ have the same units as FWHM. Using selected $\tau_{\circ}$ values and the selected pulse energy E, the peak power can be calculated by,

$$\frac{E_{\circ}}{2\tau_{\circ}} = \frac{P_{max}\sqrt{\pi}}{2} \qquad (7)$$

Thus, we obtain,

$$E_{\circ} = P_{max}\sqrt{\pi}\,\tau_{\circ} \qquad (8)$$

Where P_{max} related to laser energy, $E_{\circ}$ and pulse duration by the following equation,

$$P_{max} = \frac{E_{\circ}}{\tau_{\circ}\sqrt{\pi}} \qquad (9)$$

These formulas are used for comparison with the experimental results which will be discussed in Section 4.

3 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 CW mode and in repetitively pulsed mode. The power supply consists of 15 pins which are available at sub D male connector which is used to control and monitor the operational performance of the power supply.

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, pulse repetition time, 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.
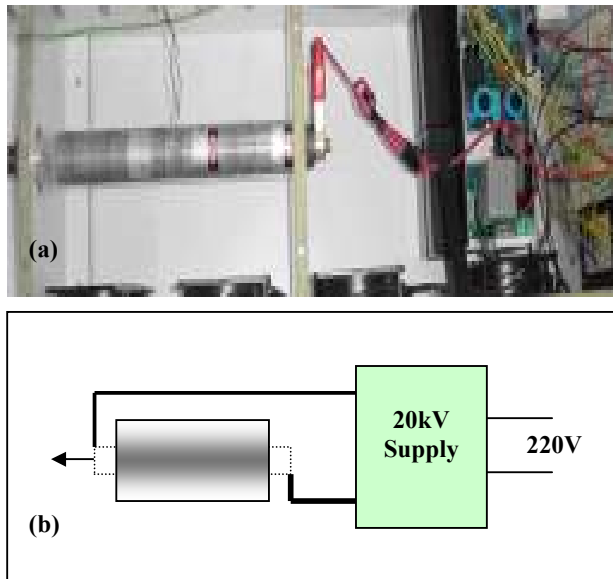
Fig. 3 (a) Top view of the laser system (b) 20 kV power supply connected to CO_2 laser tube terminal.
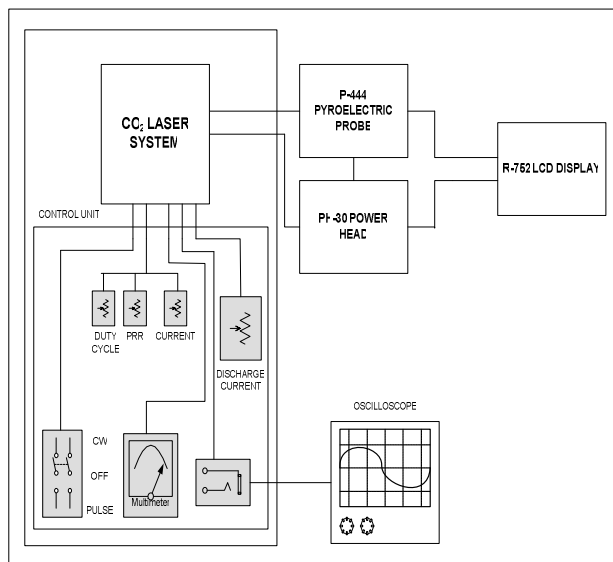

Fig.4 Block Diagram for Measurement of Output Parameters of CO_2 Laser.

4 Results and Discussions

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 or frequency and the discharge current of the laser system.

4.1 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 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.
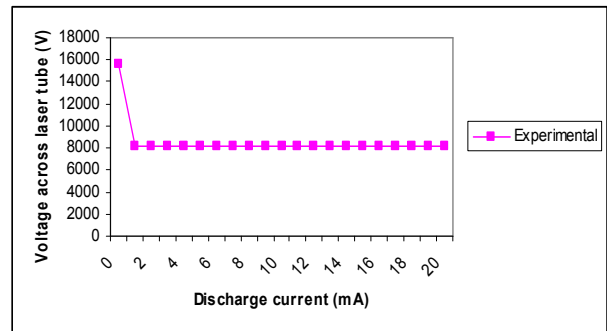

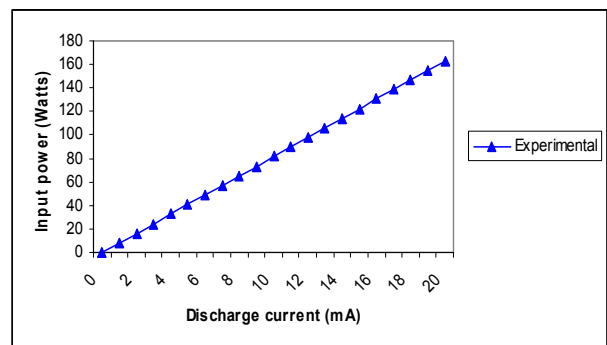Fig.5 Voltage across laser tube as function of Discharge current

Fig.6. Input power as function of Discharge current

4.2 Output Energy

The output energy of the laser system 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 was placed in front of the laser beam. The meter will automatically scale to pulse energy measurement and display the reading in joule on the LCD display. The results were illustrated in Fig.7 and Fig.8 respectively.

The pulse energy is found to increase with the increase in pulse repetition rate. The maximum pulse energy was found at 50 Hz of pulse repetition rate at 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 saturation of the molecules inside the laser tube.

After certain limit of discharge current and pulse repetition rate, the relaxation rate of lower energy level decreases. Therefore, the population density of lower energy levels increases, while those of the upper energy level decreases.

Besides that, the decrease in the on time of the input electric discharge through the lasing media will cause the population density of all the molecules in the upper level to decrease. The decrease in population density of the upper energy level could be assigned to the decrease in the output laser energy.

For the measurement of the energy as function of discharge current, again, it yielded the same results in which the maximum output energy was found at 32mJ with 50 Hz pulse repetition rate at 10mA discharge current.
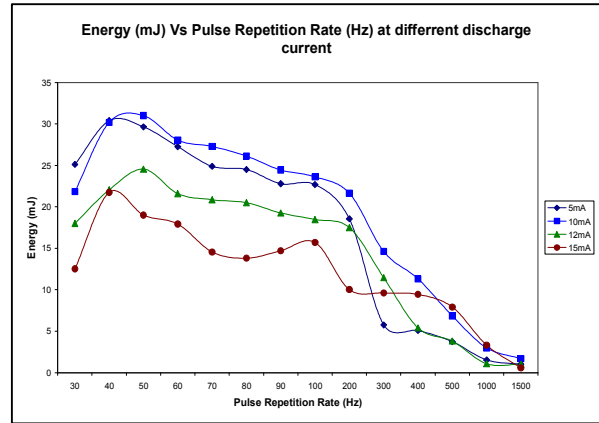
4.3 Output Power

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 continuous wave as function of discharge current can be seen in Fig.9. 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],

$$P = -0.065 I^2 + 1.796 I + 0.294 \quad (10)$$

Fig.7. Output pulse energy as a function of pulse repetition rate
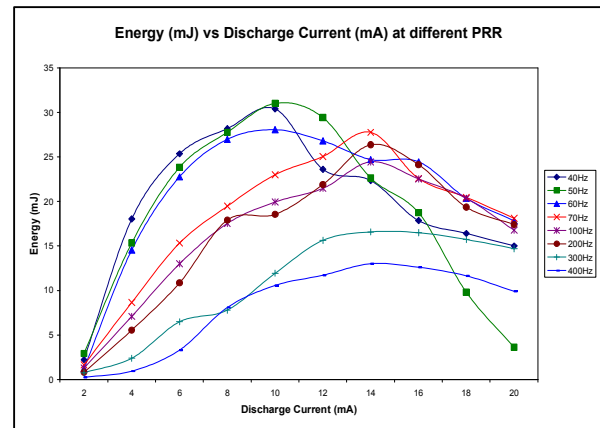
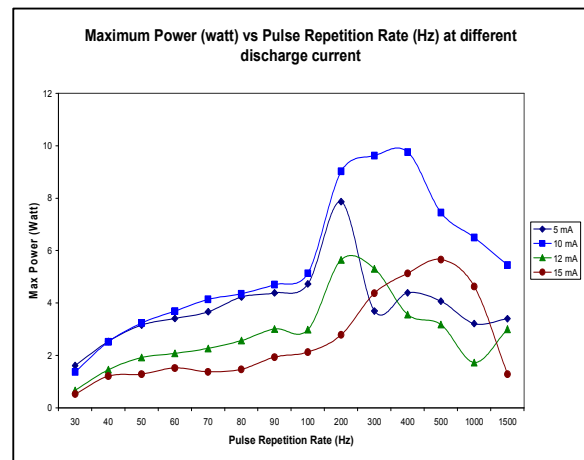Fig.8. Output pulse energy as a function of discharge current

Fig.9. Output power as function of discharge current

The results for measurements of output power in pulsed mode as function of pulse repetition rate can be seen in Fig.10.
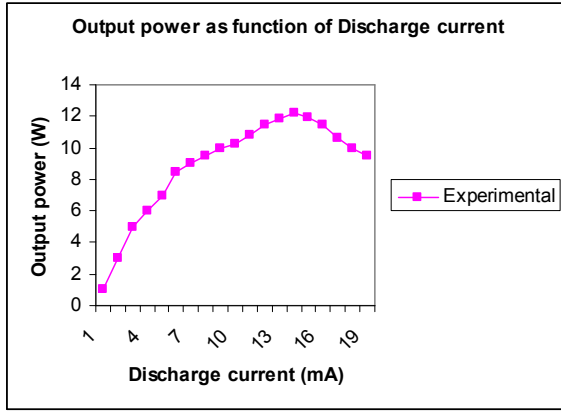
Fig.10. Maximum power as function of pulse repetition rate

An increase in maximum power has been found with increase in pulse repetition rate. The highest maximum 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 CW 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.

Fig.11 shows the results for measurement of average power as function of pulse repetition rate at different discharge current. The relationship between the maximum output power and the average power is given by,

$$P_{avg} = \frac{E}{PRT} = E \times PRR \qquad (11)$$

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. This is because the laser system became unstable due to saturation of the molecule inside the laser tube. 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 CO_2 laser in term of maximum power characteristics. The results were tabulated in Fig.12 and Fig.13 respectively. The results of experimental findings are

acceptable with percentage of total power loss less than 10%. Equation (12) gives the total power loss for experimental finding as function of discharge current [1].

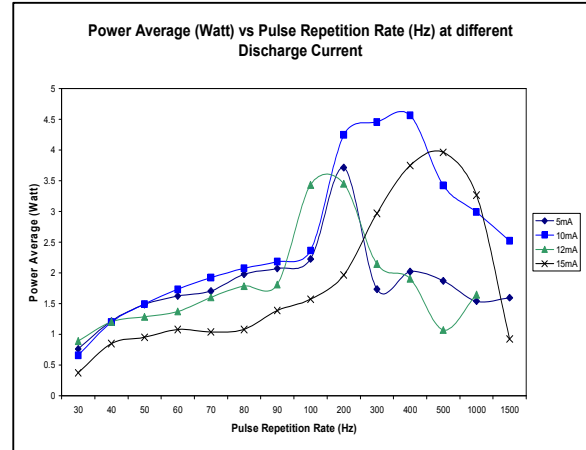$$P_{loss} = \left(-0.0657I^2 + 1.796I + 0.294 \right) \qquad (12)$$

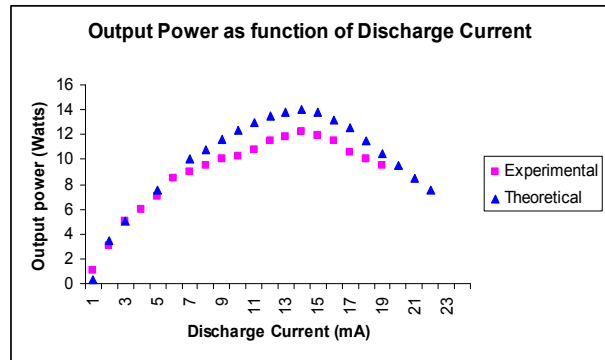Fig.11. Average power as function of pulse repetition rate

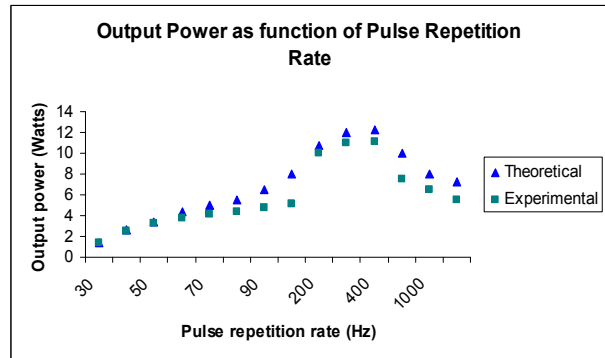Fig.12. Calculated and Measured Output Power as Function of Discharge Current

Fig.13. Calculated and Measured Output Power as Function of Discharge Current

4.4 CO_2 Laser and CNG-DI

The absorption characteristics of leaner air/ CNG mixtures have been experimentally investigated using CW/pulsed CO_2 laser at 10.6μm and were compared with pulsed Nd:Yag laser at 1.06μm and 532nm (2nd harmonic) at variable laser energy and pressures operated at 295K temperature.

The results for absorption coefficients, K_v are shown in Fig.14. As E_o or pressure increased, the absorption coefficient, K_v of CO_2 laser in CNG, air and CNG/air mixtures increased drastically in the region of E_o less than 25mJ or pressure less than about 2 to 3 bar. Depending on E_o or pressures, the absorption coefficients are in the range from $2cm^{-1}$ to about $51cm^{-1}$ for CNG, $0.85cm^{-1}$ to $48cm^{-1}$ for air and $1cm^{-1}$ to $50cm^{-1}$ for CNG/air mixtures. Again, 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.
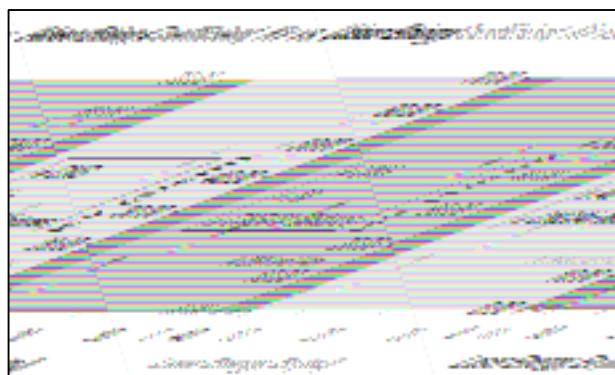

Fig.14. Absorption coefficient, K_v of CO_2 laser in CNG, air and CNG/Air mixtures on the initial laser energy, E_o

5 Conclusions

The CO_2 laser was successfully operated in continuous wave mode as well as in pulse mode to experimentally study the power and energy characteristics of CO_2 laser system at 10.6μm wavelengths. The variation in power and energy parameters of CO_2 laser have been analyzed experimentally as function of pulse time period and discharge current. The numerical results and experimental findings were compared and it is found that the results of the experimental findings are 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 CO_2 laser system in both, continuous wave and pulse mode was found stable optically and thermodynamically.

This experimental 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.

References
[1]   S. Iqbal, Fabrication of a Sealed off CO2 Gas Laser, *M. Sc Thesis,   Universiti Putra Malaysia*, 2002.
[2]   N. Khan, N.Mariun, Design and Experimental Characterization of a DC-excited CW/repetitively Pulsed Sealed Off CO2 Laser, *Optic and Laser Technology*, Elsevier Science Inc., Vol. 36, 87-94, 2004.
[3]   N. Khan, N. Mariun, N.M. Saad, Four Temperature Model of a Sealed Off CO2 Gas Laser, *Proceedings of Advance Technology Congres*s, Putrajaya, May 2003.
[4]   M.W. Scott, G.D. Myers, Steady-State CO2 Laser Model, *Appl.Opt*, Vol. 23 (17), 2374-2378, 1984.
[5]   W. J. Witteman, The CO2 Laser, Springer-Verlag, 1987.
[6]   N. Khan, N. Mariun, I. Aris, J. Yeak, Laser Triggered Lightning Discharge, *New Journal of Physics*, Vol. 4, Pg 61.1-61.20, 2004.
[7]   J.X. Ma, D.R. Alexander, D.E. Poulain, Laser Spark Ignition and Combustion Characteristics of Methane-Air Mixtures, *Combustion and Flame*, Elsevier Science Inc., Volume: 112, Pages: 492-506, 1998.
[8]   T.X. Phuoc, F.P. White, Laser-Induced Spark Ignition of CH4/Air Mixtures, *Combustion and Flame*, Elsevier Science Inc., Volume: 119, Pages: 203-216, 1999.
[9]   T.X. Phuoc, C.M. White, Optical Characterization of the Laser-Induced Spark in Air, *US Department of Energy*, National Energy Technology Laboratory, 2000.
[10] T.X. Phuoc, F.P. White, Laser Induced Spark for Measurements of the Fuel-to-air Ratio of a Combustible Mixture, Elsevier Science Inc., Volume: 81, Pages: 1761-1765, 2002.