Development of On-line Instrumentation and Techniques to Detect and Measure Particulates

Quarterly Technical Progress Report

From Jan. 1, 2003 to April 1, 2003

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Date Report was issued: Jan. 28, 2003

DOE Award number: DE-FC26-02NT41581

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Abstract

In the second quarter of the project, we build the liquid aerosol generator and characterized it. We also constructed and perfected light sources and detection systems. We also designed programs to simulate spherical particle MIE scattering for different wavelengths.

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EXECUTIVE SUMMARY

During the second quarter of this project ---- we assembled a liquid atomizer/aerosol generator and characterized the size distribution of the atomizer; we improved the performance of laser diode drivers and assembled the 10 wavelength laser assembly; we also improved the CCD camera board performance which now allow exact external timing and data acquisition; we assembled a liquid atomizer/aerosol generator; our theoretical investigation gave us a more detailed understanding of the light scattering process and we wrote computer simulation programs for the multi-wavelength scattering process based on the results.

1. We constructed the liquid aerosol generator based on the similar design we did in the first quarter, the constructed version has following features
 - Pulsed operation capability, the aerosol jet could be controlled by a solenoid valve.
 - The pressure gas backing pressure and liquid pressure are all controlled by a computer which gives us flexibility in varying our aerosol generation capability
2. We did preliminary characterization of the aerosols generated and the results indicate that mono-distributed aerosols could be generated
3. We improved the performance of the laser diode driver which could pump out over 5Amps of current, yet the rising time is about 400ns, the improvements are
 - Reduction of noise
 - Improvement of current driving capability.
4. We improved the performance of the linear CCD driver
 - The timing between the external trigger and the CCD integration is now perfectly synchronized, before we have misfiring problem
 - The noise of the CCD is suppressed by another 6dB, now we have 52dB of dynamic range.
 - By adding data acquisition to the computer, we could now automate the process of data acquisition along with aerosol generation and laser firing .
5. We constructed a multi-wavelength laser array
 - Using the off-the-shelf diode lasers and passive Q-switch lasers we constructed we build a 10 wavelength laser array.
 - The array's power could be controlled by the computer through the DAC (digital to analog converters) on an external multi-function I/O device.
 - We are still developing passive Q-switched laser harmonics (2nd, 3rd and 4th harmonics of 1064nm).
6. We build a simulation program
 - Using Visual Basic, and based on Mie scattering of spherical particles and one could change the wavelength of the laser and also the refractive index of the particles. The program generates angular distribution of the scattered light.

EXPERIMENTAL

1. Liquid aerosol generator

Similar to the designs we had in the first quarter, a liquid aerosol generator has been built at Alturdyne Power System, our industrial partner. Figure 1a shows the schematic 3D CAD and figure 1b shows the picture of the finished generator.

Figure 1a. The 3D CAD view of the aerosol generator

Figure 1b. The aerosol generator and computer controlling system.

Complete characterization of the aerosol generator is of fundamental importance in obtaining reproducible, predictable particle samples suspended in a flowing air stream, which, in turn, will define our ability to thoroughly evaluate the performance of the prototype instrument. Aerosol samples were generated using the aerosol generator and collected in a micro-orifice uniform deposit impactor (MOUDI). This allowed us to accurately calculate the aerosol mass (and number) concentration for a given experiment as a function of particle size. Aerosol characteristics were measured as a function of: Collision reservoir temperature, Collision stock solution concentration, Collision nozzle number, carrier gas flow rate and the impact of pressure. These studies will be expanded to include a range of particle compositions characteristic of exhaust particulate matters, as well as other kinds of aerosol mixtures. Our preliminary results indicate that we are able to reproducibly control the size distribution and concentration of polydisperse aerosol from our generator as a function of operating conditions. Figure 2 is illustrative of the results obtained with our aerosol generator. The standard deviation within each size fraction typically is better than $\pm 5\%$, which is remarkable. We will further our characterization with the MOUDI and the results will form the standard basis for our laser scattering devices.

Figure 2. Particle size distribution as a function of concentration (0.25 mM sodium fluorescein, 10 °C, 5 L-min⁻¹ carrier gas flow, diluted to 30 L-min⁻¹, 24 psi pressure)

2. Multi-wavelength laser sources

We build an assembly with 10 lasers at different wavelengths.

Wavelength	635nm	650nm	660nm	780nm	810nm	830nm	980nm	355nm	532nm	1064nm
Power (mW)	30	40	30	80	200	30	30	14	30	200
Package	TO	Cir. TO	Cir. To	Bare	C-mnt	TO	FC	DP/PQS	DP/CW	DP/CW

Note: Cir.TO: Circular output (from Blue sky) in a TO can, C-mnt: C-mount bare chip, FC: Fiber coupled, DP/CW: Diode pumped CW operation (could be modulated at low frequency up to 10kHz), DP/PQS: 355nm laser source is generated through harmonics of 1064nm, which is from a Diode pumped, Passively Q-Switched laser, this is still under development.

First 7 of these 10 lasers are simple diode lasers we acquired in the first quarter. They have output power under 200mW, and need current under 250mA. We use the commercial off the shelf constant current laser diode driver (LD1255) from Thorlabs to drive these diode lasers. These laser diode drivers' current setting could be set with external voltage. We wire the external voltage input pins (0 to 5V for full current range control) to the output of a multi-function ADC/DAC card (6023E) from National Instrument. In this way, one could set the diode laser power from the control computer. In

the future, these constant current LD1255 drivers could be replaced by the diode drivers that we developed below, which could provide constant power operation.

The other 2 wavelengths at 532nm and 1064nm need drive current over 1A, and we are currently using the diode driver that is described below.

In the first quarter, we build a laser diode driver that could pump out 5A current and switching time well under 1 μ s. This driver could also operate under constant power mode with external photo-diode feedback. The first generation of this diode driver, although meet the specifications desired, has high transient noise when the current is not turned on. We located the noise sources in the second quarter after building 3 modified versions. The first kind of noise is from the feedback of second diode driver chip --- when the OPAM chip between the first (master) and the second (slave) diode driver chips could not drive high enough current. We solved this problem by using a TLV2372 (from Burr-Brown/TI, ± 100 mA) OPAM, while the previous OPAM chip is OPA4350 (from TI, $\sim \pm 40$ mA) has noise problem. The second kind of noise is from the cooling fan on top of the heat sink of the diode driver chip (WLD3343, Wavelength Electronics). The obvious coupling between the fan (due to inductance change when the fan operates) and the chip's current is obvious when we relieve the fan from the heat sink by only 0.1". Now, we use a plastic spacer to separate the fan from the heat sink, and the noise disappeared.

Figure 3a. Improved LD+TC driver box.

Figure 3b. Schematic of improved LD+TC driver box.

	L1(mm)	L2(mm)	S1	S2
Configuration 1	0.75	0.25	HR1064, HT808	R=25% 1064
Configuration 2	1	1.5	HR1064, HT808	AR/HT 1064
Configuration 3	3	1.5	HR1064, HT808	AR/HT 1064
Configuration 4	3	3	HR1064, HT808	R=25% 1064

We also have built a passively Q-switched laser using the optics we acquired in the first quarter. The goal here is to generate higher harmonics of 1064nm so we could have laser wavelengths in the UV. In the first quarter, we have also acquired optics for construction of the 355nm and 266nm sources, these optics are based on passively Q-switched lasers (Cr:YAG and Nd:YAG) and the configurations are listed in the table above. We also use a C-mount 810nm laser diode to pump the first configuration. The laser diode is directly butt-coupled to the optics with no collimation and focusing lenses, and an external output coupling mirror is placed about 1" away to further lower the threshold of the operation. With a 2W laser diode, we obtain laser pulses as short as 15ns, 4.7kHz and 150mW of 1064nm power. The pulse width is characterized by a fast photodiode connected to the 1GHz digital oscilloscope in our lab (figure 4). This ultra-short pulse squeeze in about 30 μ J of energy in 15ns time, and the peak power is over 2kW and the power density is well over MW/cm² even without focusing, this kind of high peak power density allows efficient doubling and tripling harmonics generation. We are right now working on this direction. The other 3 configurations should give even more power by reduction in pulse width and increase in pulse energy. We hope to generate ~10mW of 355nm for the particulate study.

Figure 5. Schematic for the diode pumped passively Q-switch laser

In all configurations, S1 and S2 have parallelism within 5sec, cross sections of 3x3mm. Cr:YAG has absorption about 6cm^{-1} at 1064 nm. The 4 combinations above should give us laser pulses with pulse width ranging from 300ps or less to 4ns, and pulse energy from 10 μJ to 300 μJ .

3. Array detector

We also have perfected our linear CCD array detector. In the first quarter, the CCD array detector controller board for the ELIS1024 chip would sometimes miss firing the DATA trigger, therefore providing false signal. We solved this problem with newly designed control logic. We are evaluating the ultra-short integration time capability of the ELIS chip and our goal is to use this ultra-short integration time to synchronize probing laser pulse with the signal detection, reducing the integration time when there is no laser present. This will reduce the noise accumulated over long integration time and therefore reduce the requirement on ambient light blackout.

Figure 6a. Schematic of ELIS board

Figure 6b. Schematic of the improved ELIS controller board

Figure 6b. The ELIS board is clamped on the post (back) and the controller board (with 3 white BNC terminals) are shown along with the collimation lens (front) and softly-focusing lens (back, before the ELIS board) assembly. Light scattering signal will first be collimated and then softly focused before collected by the ELIS board. We will add a diffractive optics in between the collimation lens and the softly-focusing lens later for multi-wavelength operation.

RESULTS AND DISCUSSION

1. Experimental results

We successfully constructed a liquid aerosol generator that is designed to repeatedly generate monosize liquid aerosols at will. The aerosol generator is controlled through a computer. This automated process gives more flexibility and automation to the experiment. The preliminary test results indicate that monosized aerosols are generated repeatedly. We are conducting further test on the aerosol generator to determine its capability when we tune the pressure, the gas feed rate and temperature. This kind of calibration will give us the standard for our light scattering measurement in the next phase.

2. Theoretical simulation and literature review

We developed code based on the basic Mie scattering theory. Using Visual Basic, we wrote interactive program that allow one to change the wavelength easily and generate the angular distribution of the scattered signal. The preliminary result is consistent with the results in the reference book (ref. 1). The other variables that could be changed at will include refractive index of the particles so that one could change the absorption properties of the particles. However, the program is based on Mie scattering on spherical shaped particles, and we are adding code based on references (ref. 2) so we could simulate other more practical particles with different shapes, e.g. cylindrical rod and discs.

We need to add functions to the current program. This extra functions needed are:

- Generate scattering pattern from an array of laser wavelengths, this will be needed to compare with results in the final experimental setup
- Generate scattering pattern when the lasers are shooting in from different angles. This will give us flexibility in our next phase when we compare multi-wavelength light scattering signal with single-wavelength light scattering signal, i.e. we could either shoot in lasers from the exact same direction which requires pre-combination of the lasers, or for simplicity, we could shoot in the lasers from slightly different angles.

HYPOTHESIS AND CONCLUSIONS

This past quarter proceeded as planed and we finished the construction of the aerosol generator and the preliminary test results are satisfactory. The results are consistently repeatable and meet our expectations. We also improved the performance of the laser drivers with high current output and fast rise time. We constructed a diode pumped passively Q-switched laser and get pulse width as short as 15ns and pulse energy of $\sim 30\mu\text{J}$ at 1064nm. The multi-wavelength laser array is constructed and ready for the scattering experiment. We improved the CCD array controller which now give us capability to integrate over very short period of time and free from misfiring. In theoretical modeling, we developed code that repeat the Mie scattering results and could let one change the input wavelength and generate corresponding scattering pattern.

Reference:

1. Absorption and scattering of light by small particles, Craig F. Bohren, Wiley Inter. Science, 1998, 1st edition.
2. “Light scattering calculations for irregularly shaped axisymmetric particles of homogeneous and layered compositions”, John P. Barton, Special issue in Meas. Sc. Tech. Vol. 9, 151-160, 1998

Appendix:

Planned schedule from the statement of work

Task	Technical Milestone	Schedule
1. Assembly of the multiwavelength light source	Ready diode & DP chip lasers, drivers	Month 1-6
	Ready beam combination system	Month 1-6
2. Construction of the PM synthesizer	Verify that monosize PM are generated	Month 1-6
3. Simulation of Rayleigh and Mie Scattering	Literature review	Month 1-3
	reviewComputer program that could generate simulated scattering spectrum	Month 1-6
4. Laboratory demonstration of instrument	Experimental scattering spectrum database for different PM sizes	Month 7-18
	Compare with theory and conventional PM monitoring data	
5. Application of the PM analyzer to a combustion environment: engine intake area	Correlation of our instrument data with conventional PM monitoring data	Month 13-24
6. Application of the PM analyzer to a combustion environment: engine exhaust	Correlation of our instrument data with total PM mass emission, new data (PM size and chemical composition) about in-situ PM monitoring	Month 13-24
7. Applicability assessment for PM emissions from coal fired power plants	Design/modify our PM instrument for smoke stack PM monitoring	Month 24-30
8. Instrument design optimization	Optimize the instrument during different experiments	Month 13-36