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BNL-73723-2005-IR

Variable Firing Rate Oil Burner Using Pulse Fuel Flow Control

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October 2004

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Managed by
Brookhaven Science Associates, LLC
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Contract No. DE-AC02-98CH10886

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1.0 Introduction

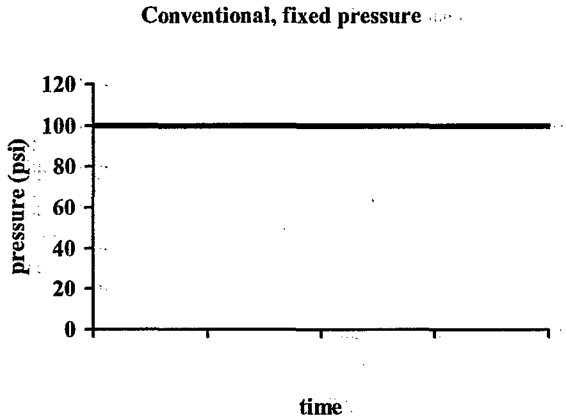
1.1 Background

The residential oil burner market is currently dominated by the pressure-atomized retention head burner, which has an excellent reputation for reliability and efficiency. In this burner, oil is delivered to a fuel nozzle at pressures from 100 to 150 psi. In addition to atomizing the fuel, the small, carefully controlled size of the nozzle exit orifice serves to control the burner firing rate. Burners of this type are currently available at firing rates of more than 0.5 gallons-per-hour (70,000 Btu/hr). Nozzles have been made for lower firing rates, but experience has shown that such nozzles suffer rapid fouling of the necessarily small passages, leading to bad spray patterns and poor combustion performance. Also, traditionally burners and the nozzles are oversized to exceed the maximum demand. Typically, this is figured as follows. The heating load of the house on the coldest day for the location is considered to define the maximum heat load. The contractor or installer adds to this to provide a safety margin and for future expansion of the house. If the unit is a boiler that provides domestic hot water through the use of a tankless heating coil, the burner capacity is further increased. On the contrary, for a majority of the time, the heating system is satisfying a much smaller load, as only rarely do all these demands add up. Consequently, the average output of the heating system has to be much less than the design capacity and this is accomplished by start and stop cycling operation of the system so that the time-averaged output equals the demand. However, this has been demonstrated to lead to overall efficiencies lower than the steady-state efficiency. Therefore, the two main reasons for the current practice of using oil burners much larger than necessary for space heating are the unavailability of reliable, low firing rate oil burners and the desire to assure adequate input rate for short duration, high draw domestic hot water loads.

One approach to solve this problem is to develop a burner, which can operate at two firing rates, with the lower rate being significantly lower than 0.5 gallons per hour. This paper describes the initial results of adopting this approach through a pulsed flow nozzle.

1.2 Pulsed Flow Concept

The two-stage burner operation is to be achieved thus. At the high firing rate, the flow of oil to the conventional pressure atomized burner nozzle will be continuous. The low firing rate is achieved by the cycling of the flow on and off at a high frequency, so that the average flow rate corresponds to it. Ideally, under low-fire operation the fuel will arrive at the atomizer in sharp, high-pressure pulses as illustrated in Figure 1. The fuel pulses must be sharp, as the atomization of fuel at lower pressures, which would occur with "blurred" pulses, would result in large fuel drops and poor combustion. The high operating frequency ensures that the flame is not 'quenched' and hence the operation is fundamentally different from on-off cycling. The low firing rate can be adjusted by changing the pulse widths, called pulse width modulation (PWM).



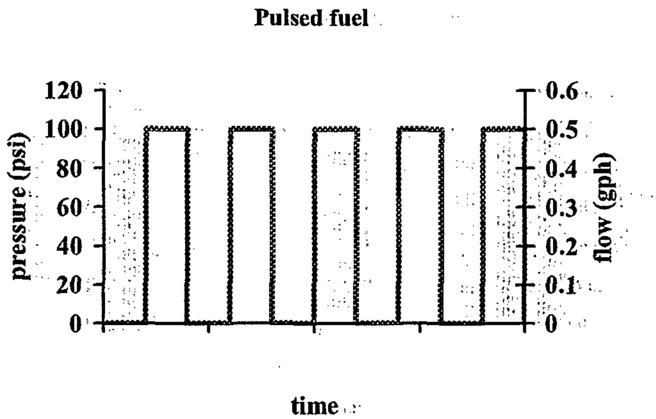


Figure 1. Ideal Normal and Pulsed Fuel Flow through a Pressure Atomizer.

Prior U.S. work has been done in this area in which the fuel flow pulses were achieved by a specially designed fuel pump [1,2]. That system has not been commercialized. Some work has been done in France [3] to modulate the flow from a liquid fuel injector for the purpose of active combustion control. The injector flow and spray properties were characterized, but no tests to assess the combustion performance were reported. The injector was a standard pressure atomizing nozzle (European) used in residential boilers and the modulation was imposed by a solenoid valve mounted immediately upstream of the nozzle to minimize the liquid volume trapped between. The valve was specially fabricated and had quite a small response time of about one millisecond. A small response time is needed to drive the fuel pulsing at a high enough frequency to maintain stable combustion. The pulsed mode tests were carried out at two frequencies, 60 Hz and 600 Hz. At 600 Hz, they found that the flow rate modulation was quite small, of the order of 5%. While this may be useful as input to active control, it is not of significance for flow modulation of interest here. At 60 Hz, the average flow rate was reduced to about 60 % of the value when the valve is open continuously, although this was not of interest to the researchers. They also measured the temporal variation in the fuel flow rate and an interesting observation from these measurements was that the maximum flow rate when the valve was open is less than the flow rate with the valve open continuously. Even more interesting was the observation that the flow rate was about half this value and not zero when the valve was 'closed'.

2.0 Present Work

2.1 Valve in Line

The pulse width modulation approach was initially implemented by the cycling operation of a solenoid valve in the fuel supply line similar to the work described above. The low mass valve and the drive circuit were supplied by the Lee Company. The valve was customized to fit our requirements and uses a complex circuitry to drive the low mass valve's solenoid. The packaged control circuit provided by the manufacturer, supplies the normal operating voltage of 12 volts DC for a short period to open the valve and then drops it to an average holding voltage of about 3 volts. This helps to prevent overheating of the low mass valve. The circuitry can be used to change the frequency of opening and closing of the valve and also the duration of opening giving pulse width modulation at different operating frequencies.

2.2 Cold flow Tests

Initial tests with the valve were cold flow tests to determine the range of flow modulation possible while cycling at high enough frequencies. Figure 2 is a schematic of the experimental set-up used for the cold flow tests.

The importance of sharp pressure pulses was emphasized above. In order to measure these pressure pulses, a fast response pressure transducer was installed in the test system just before the nozzle. The transducer has a small and thin diaphragm that flexes in response to the transient fuel pressures. This flexing is converted to electrical voltages by strain gauges. This voltage output was measured by a digital storage oscilloscope, which can store the data internally and on magnetic media. The oscilloscope can also be used to perform a Fourier analysis using a Fast Fourier Transform feature. The characteristic of the nozzle spray under pulsing operation was determined using the Malvern Spray Analyzer. Home heating oil (ASTM #2 fuel oil) was used in the tests.

The solenoid valve was tested in combination with a 0.5 gallon per hour (gph) nozzle. After a series of preliminary tests, a cycling rate nominally of about 60 Hz (58 Hz as measured) was chosen to do the tests. The tests were run at three different operating pressures that span the range of normal operating pressures with such nozzles in residential systems. The modulation in the flow achievable with pulse width modulation at the different pressures was measured. The results are given below in Figure 3. At 85% pulse width, that is the valve open for 85% of the time in the cycle nominally, the flow reaches the design value of 0.5 gallons per hour at 100 psi pressure. It is also seen that the flow variation achievable is slightly higher at the higher pressures and a flow ratio of between 1:3 and 1:4 was achieved.

As mentioned earlier, the transient pressures that are impressed on the nozzle due to the operation of the valve can be significant for the quality of the atomization and were measured with a pressure transducer. The result from one such measurement at the same operating frequency of 58 Hz and a pulse width of 50% in the cold flow test set-up is shown in Figure 4 below. It can be seen that the pressure rise and fall are not nearly as steep as one would possibly like them to be. It can also be seen that the pressure has not fallen to zero when the valve has ostensibly shut off and so presumably the flow has not either. This is similar to the result reported in reference 3, Haile et al, and mentioned above. This does suggest the need for improvement in performance of the system.

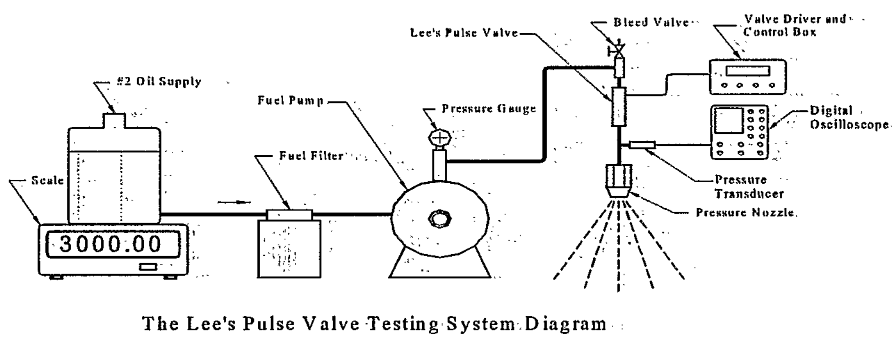


Figure 2. Schematic of Cold Flow Test set-up.

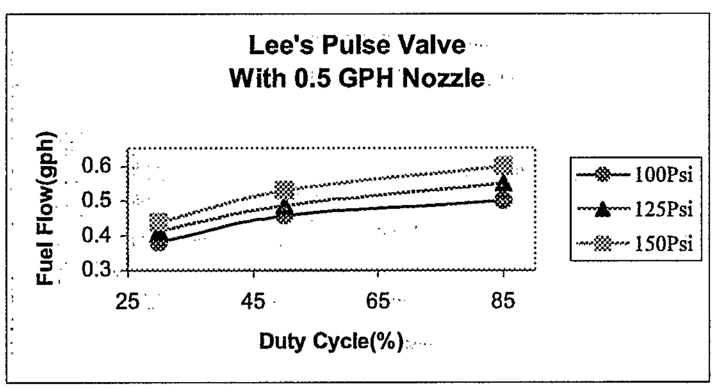


Figure 3. Fuel Flow Variation by Pulse Width Modulation

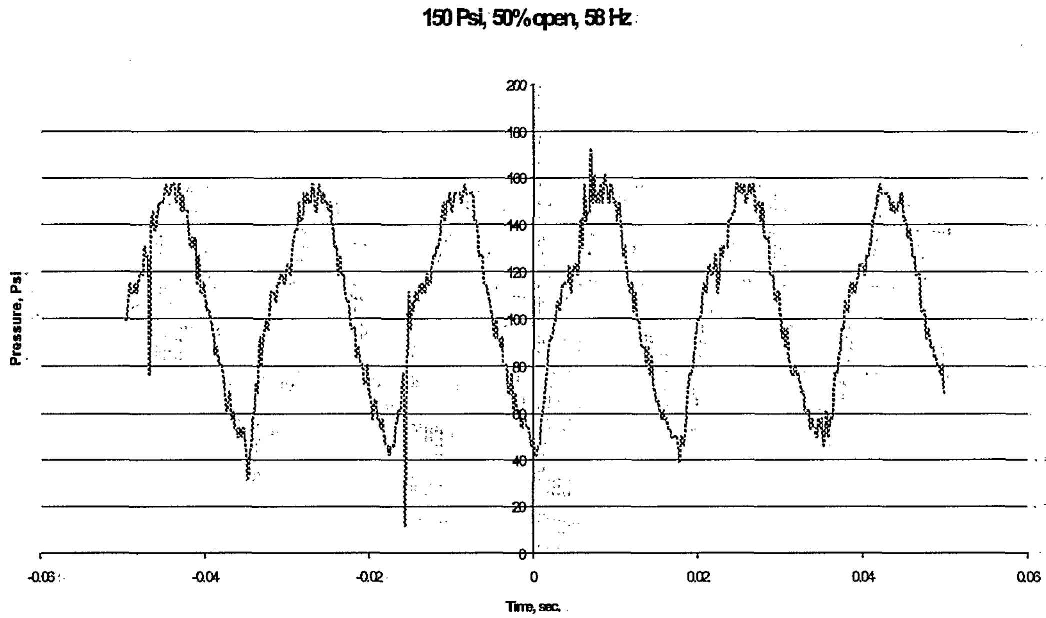


Figure 4. Transient Pressure Measurements in Cold Flow

Finally, it is important to know whether the quality of the atomization is maintained on the average as the fuel flow is modulated. As indicated above, this was measured using the Malvern Spray Analyzer. A summary of the results in terms of the volume mean diameter for the sprays generated with different pressures and different duty cycles are given in figure 5 below. As expected for a pressure nozzle, the mean diameters are reduced by increase in operating pressure. Also, it is seen that the mean diameter increases with reduction in the duty cycle suggesting decrease in the quality of the atomization with reduction of the flow. This effect seems to be more pronounced at a pressure of 100 psi than at the highest tested pressure of 150 psi. This might suggest that the deterioration in performance is due to a combination of the effects of changes in the performance of the nozzle and changes due to the operation of the valve including possibly the non-zero cut-off pressure noted above. Again, this deterioration in performance seems more pronounced at 100 psi pressure, a mean diameter ratio of 1.41, than at 150 psi where the mean diameter ratio is 1.28.

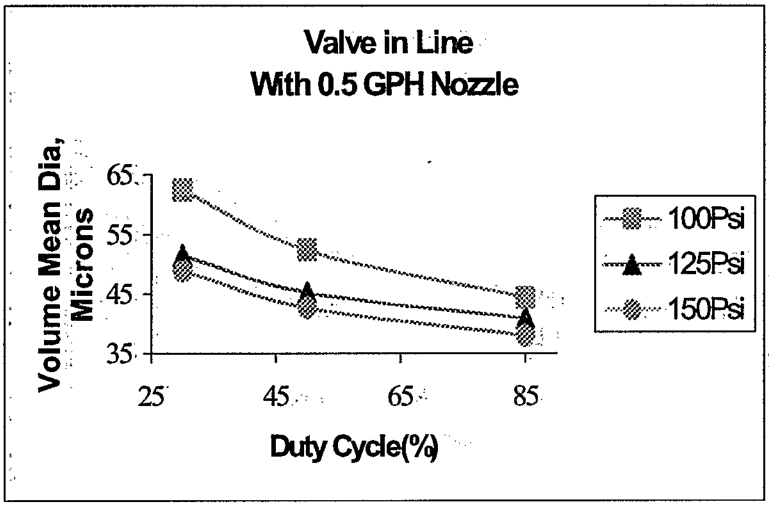


Figure 5. Droplet mean Diameters for Sprays

2.3 Combustion Tests

Even though the performance with the inline nozzle was not entirely satisfactory, it was decided to conduct preliminary combustion tests to determine how the valve and nozzle combination would perform in a residential boiler setting. A modern retention head burner and a wet base boiler were used for the tests. The same nozzle and valve in line combination were assembled in the burner. The usual measure of performance, which is the smoke limited excess air, was determined at the highest and the lowest flows. The tests were carried out at the maximum flow rate (maximum duty cycle) and at the minimum flow rate attainable at a fuel flow. Results from this preliminary testing are illustrated in Figures 6 and 7 below. (The fractional smoke numbers are obviously not measured values but are there for illustration.). They show the effect of excess air on the flue smoke numbers at the lowest and the highest firing rates. From comparing the two figures, it can be seen that, at the lower firing rate, smoke starts increasing at a higher excess air. This effect might be a result of burner characteristics (the burner is nominally designed for the higher flow rate) and of the degradation in atomization characteristics noted above. It was also noticed during the tests that it was difficult to achieve stable ignition under the low flow conditions and hence an operational requirement may be to start under the higher firing rate and then switch to the lower. However, no attempts were made to optimize the system, as these were only preliminary tests and were only intended to demonstrate that such a pulsed flow system could be made to work in a residential boiler.

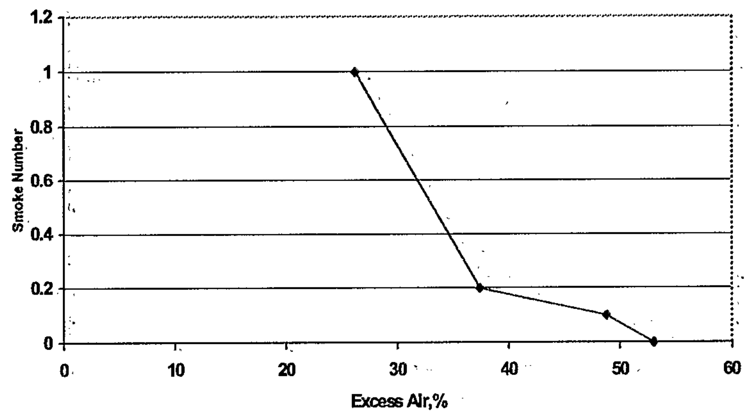


Figure 6. Smoke versus Excess Air at the Lowest Flow Rate

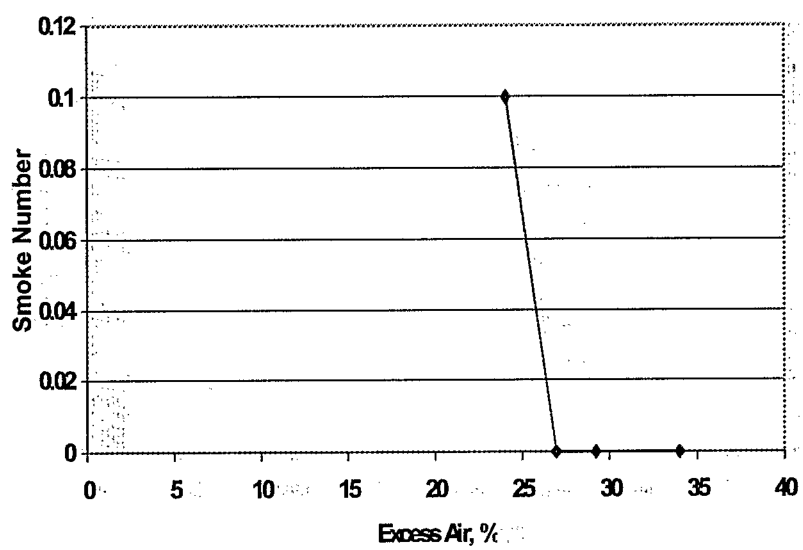


Figure 7. Smoke versus Excess Air at the Highest Flow Rate

3.0 Integrated Valve and Nozzle System

Following the successful demonstration of the valve in line system, it was suggested that the performance could be improved by reducing the fluid volume trapped in the volume between the valve and the nozzle. For this reason, it was decided by the

Lee company design engineer to integrate the valve into the pressure atomizer nozzle. For this application, a nozzle with a nominal rated flow of 0.85 gallons per hour was chosen to integrate with the valve and this is in significantly higher than the 0.5 gph used in the earlier valve-in-line tests. This leads to a couple of factors that need to be considered when examining the test data. The atomization quality given by the mean drop sizes will be different because of the different flow rates. Also, as will be seen from the flow data below, the integrated valve and nozzle has a flow smaller than the nominal 0.85 gph for the stand-alone nozzle and this could affect the atomization quality as well. Also, in the combustion tests, the valve was operated at a frequency of about 200 Hz, which is significantly higher than the previous tests at 58 Hz. This was done in the hopes of improving the combustion performance at the low flow rates.

Figure 8 below is a photograph of the valve integrated into the pressure nozzle. Two electrical leads that connect to the power supply and control for the valve can be seen along with the fuel connection in the middle.

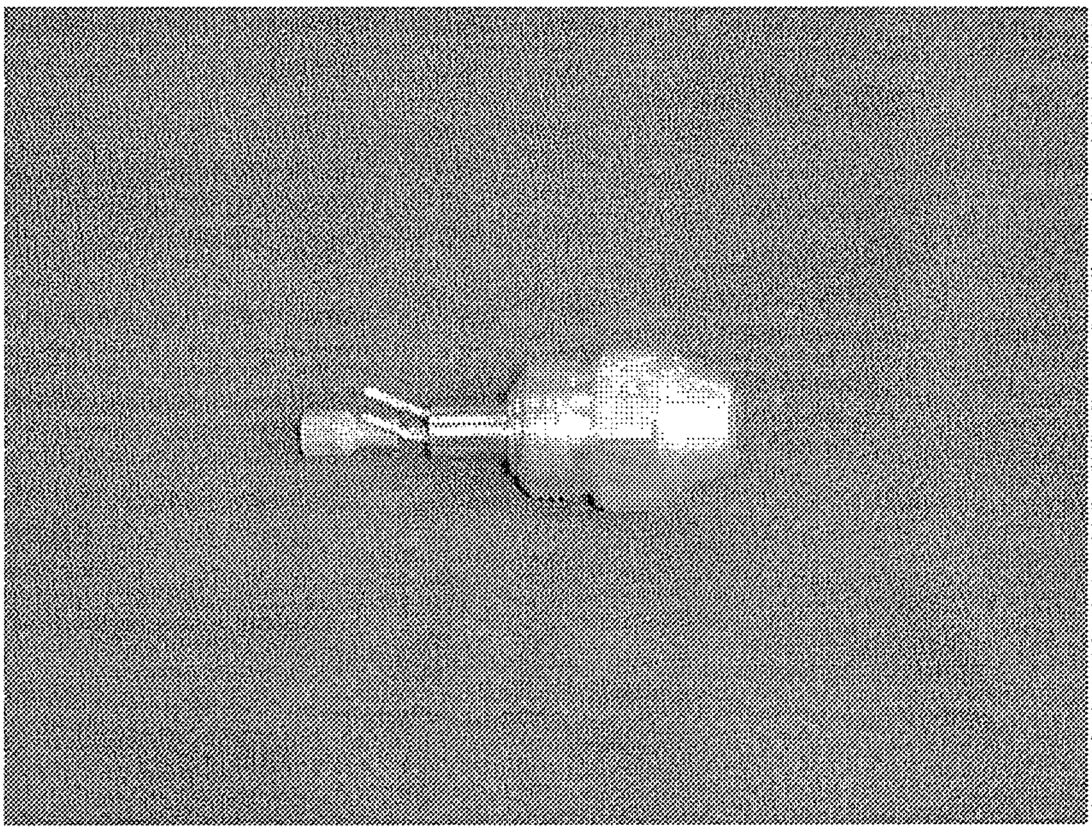


Figure 8. Valve integrated in the Nozzle

Figure 9 shows the valve-in-nozzle of figure 8 assembled into the fuel tube of the burner. This assembly makes possible the disposition of the fuel supply line and the electrical lines to the valve within the air tube of the burner so that the burner can be assembled normally.

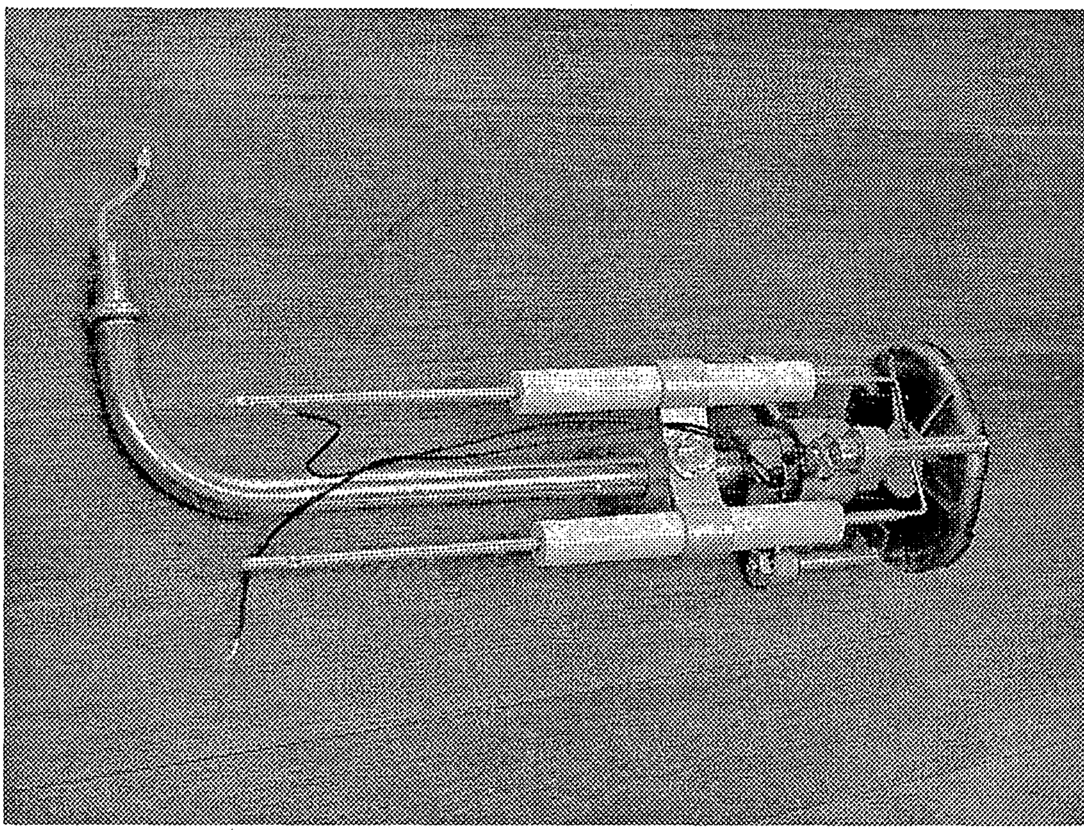


Figure 9. Valve-in-Nozzle in Fuel Tube of Burner

3.1 Cold Flow Tests

As before, the new valve-in-nozzle system was tested in the cold flow test set-up for its flow and atomization characteristics. As before, the fuel pressure was varied and the flow rate was determined at different duty cycles. It was felt that, as the combustion performance with the previous version of the valve at the low flow rate was not very good, it would be beneficial to operate at a higher frequency. Hence, all the cold flow and combustion tests reported on below were conducted at a frequency of 200 Hz. No pressure transducer measurements were conducted with this valve-in-nozzle combination. The results are summarized below in two figures. Figure 10 shows the range of flows attainable at the three pressures of 100 psi, 125 psi and 140 psi. In all cases, the maximum to minimum flow ratio achievable is a little over 1.7. This does constitute an improvement over the previous case of about 1.3 to 1.4 and seems to bear out the manufacturer's suggestion for improving the performance in this regard.

The atomization characteristics were also measured and are given below in figure 11 as a plot of the volume mean diameters under different conditions. We see the expected improvement with increase in operating pressure and deterioration with reduced flow (lower duty cycle). As before, the latter is less pronounced at the higher pressure of

140 psi. It can also be seen that the mean drop sizes are higher than those in the previous case due to the factors mentioned above.

The flow modulation and atomization characteristics appear to be reasonable, especially for a first prototype. Hence, the modulating system was tested for combustion performance.

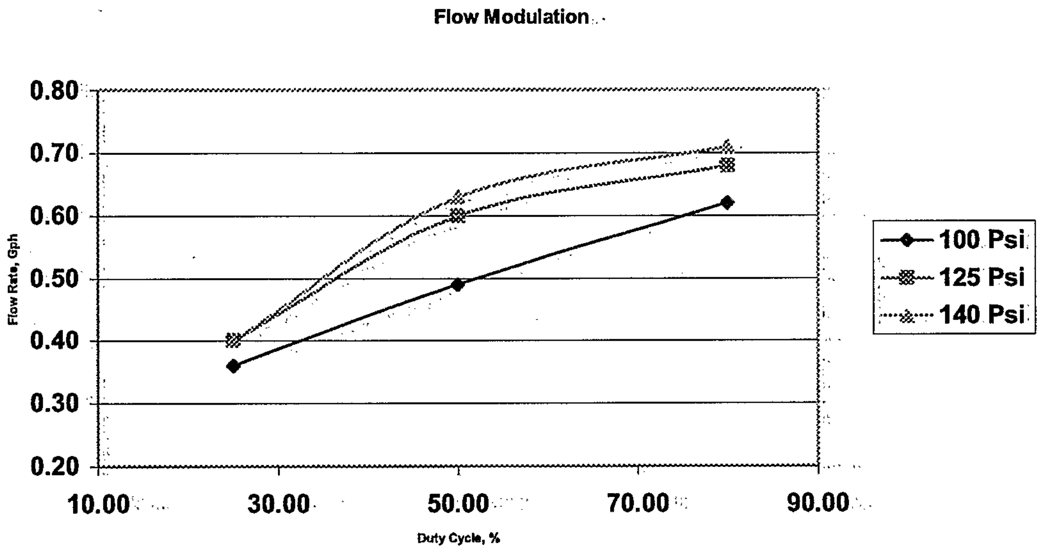


Figure 10. Flow Characteristics of Valve-in-Nozzle System

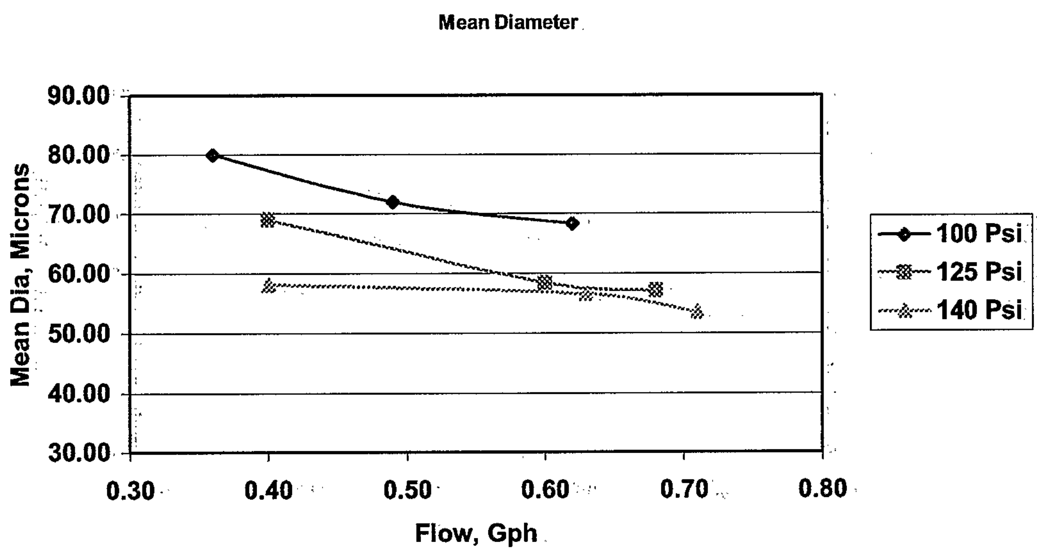


Figure 11. Droplet Mean Diameters for Sprays

3.2 Combustion Tests

The valve shown in figure 9 was assembled in the same burner used in the previous tests and tested also in the same boiler. The performance will be represented here by the Carbon monoxide (CO) emission in the stack. Figure 12 below is one set of results that shows a couple of things. As noted before, the performance is worse at the lower duty cycle and the lower flow as the CO levels are higher and the range of operation at reasonable CO levels is smaller. Overall, the CO levels are also higher even at the 80 % duty cycle than with a conventional nozzle at similar flow rates. The reasons are probably many, including the change in atomization characteristics due to the factors mentioned earlier, and possibly the retrofitting to an existing burner.

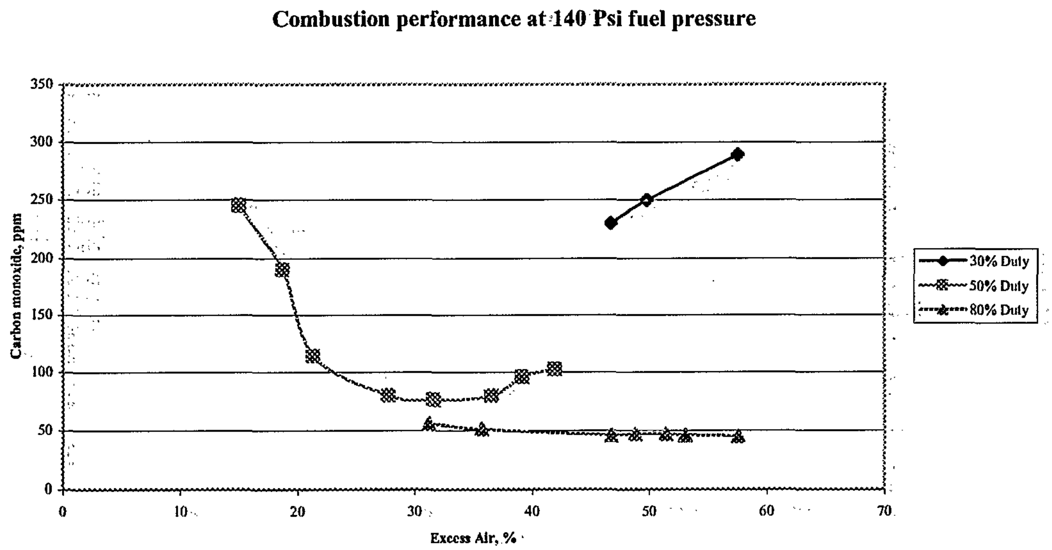


Figure 12. Combustion Performance of valve-in-Nozzle system

The photographs below are of the flames seen from the end of the boiler in the tests above and illustrate the differences between the high and low flow conditions. It can be seen that there is relatively a more extensive 'dark' region in the cross section for the low flow flame than for the high flow flame. This seems to suggest a more extensive soot production (reflected in the smoke numbers which were higher) and meaning more incomplete combustion reflected in higher carbon monoxide emissions.

Figure 13: Flame for the High Fuel Flow Rate

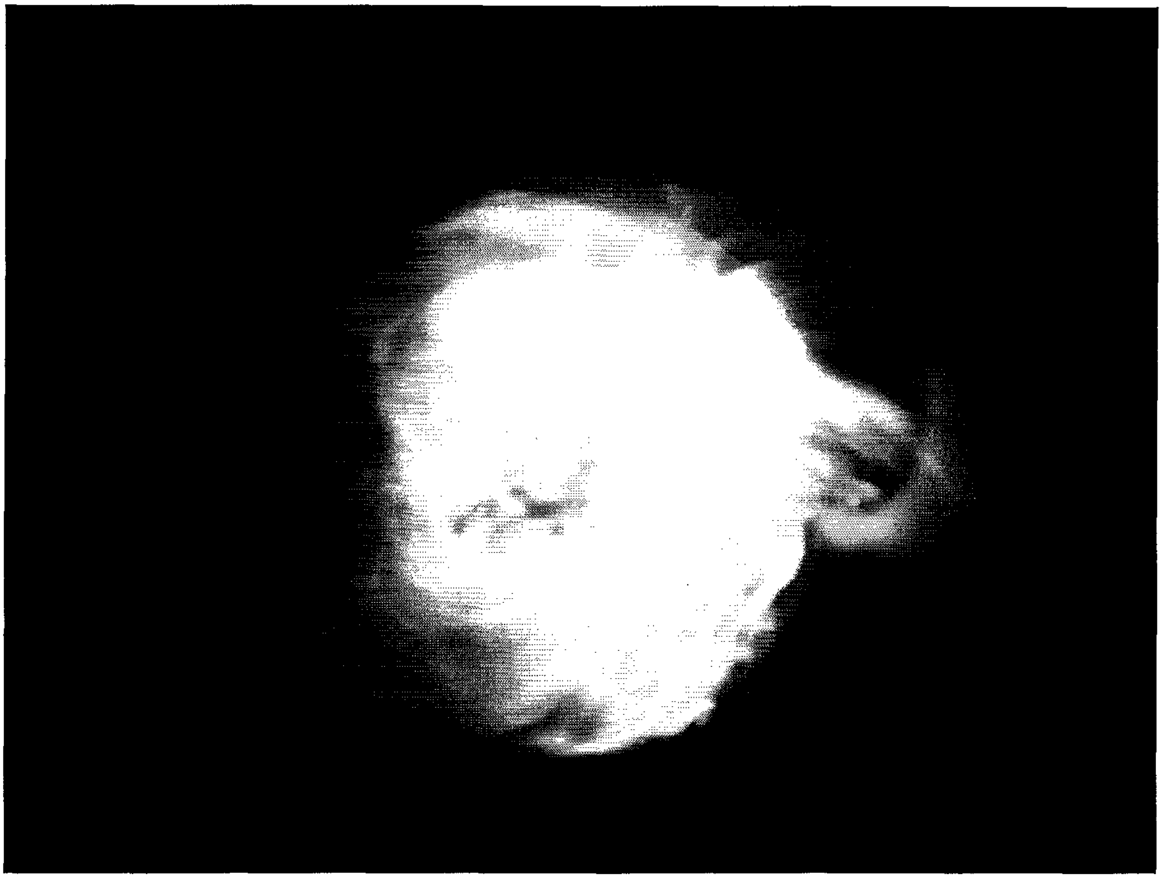


Figure 14. Flame for the Low Fuel Flow Rate

4.0 Conclusions and Recommendations

It has been shown that the concept of flow modulation with a small solenoid valve is feasible. Especially in the second configuration tested, where the Lee valve was integrated with the nozzle, reasonable modulation in flow of the order of 1.7 could be achieved. For this first prototype, the combustion performance is still not quite satisfactory. Improvements in operation, for example by providing a sharp and positive shut-off so that there is no flow under low pressures with consequent poor atomization could lead to better combustion performance. This could be achieved by using nozzles that have shut off or check valves for example. It is recommended that more work in cooperation with the valve manufacturer could produce a technically viable system. Marketability is of course a far more complex problem to be addressed once a technically viable product is available.

5.0 Acknowledgements

The experimental work was accomplished with the able help of Yusuf Celebi and George Wei. Mike Curtis of the Lee Company was instrumental in providing the hardware, including integrating the valve with the nozzle and was helpful with useful suggestions during the entire work with the Lee solenoid valve. The New York State Energy Research and Development Authority (NYSERDA) is acknowledged for funding the project, which resulted in this report. We thank the program manager at NYSERDA, Ray Albrecht for providing valuable suggestions, and consistent encouragement during the course of the project.

6.0 References

1. Hunsberger, D., Suntec Industries, personal communication with T. Butcher.
2. U.S. Patent 4391580, Liquid Fuel Supply for an Atomization Burner Nozzle, Assigned to Sundstrand Corporation. (1980).
3. Haile E., Lacas F., Desrayaud C., Veynante D., Durox D., Characterization of a Liquid Fuel Injector under Continuous and Modulated Flow Conditions, Part. Part. Syst. Charact. *15* (1998) 136-144.
4. C.R. Krishna and Michael Curtis, Variable Firing Rate Oil Burner Using Pulse Fuel Flow Control, Proceedings of the 2001 National Oilheat Research Alliance Technology Conference, Brookhaven National Laboratory (2001).