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RESIDENTIAL OIL BURNERS WITH LOW INPUT AND TWO STAGE FIRING

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ABSTRACT

The residential oil burner market is currently dominated by the pressure-atomized, retention head burner. At low firing rates pressure atomizing nozzles suffer rapid fouling of the small internal passages, leading to bad spray patterns and poor combustion performance. To overcome the low input limitations of conventional burners, a low pressure air-atomized burner has been developed which can operate at firing rates as low as 0.25 gallons of oil per hour (10 kW). In addition, the burner can be operated in a high / low firing rate mode.

Field tests with this burner have been conducted at a fixed input rate of 0.35 gph (14 kW) with a side-wall vented boiler/water storage tank combination. At the test home, instrumentation was installed to measure fuel and energy flows and record trends in system temperatures.

Laboratory efficiency testing with water heaters and boilers has been completed using standard single purpose and combined appliance test procedures. The tests quantify benefits due to low firing rates and other burner features. A two stage oil burner gains a strong advantage in rated efficiency while maintaining capacity for high domestic hot water and space heating loads.

Key Words: Oil-Fired, Space Heating, Burner, Atomization, Residential, Testing, Boiler, Hot Water

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DISCLAIMER

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INTRODUCTION

The residential oil burner market is currently dominated by the pressure-atomized, retention head burner. In these burners, oil is delivered to a fuel nozzle at pressures from 100 to 150 psi (690 to 1000 kPa). In addition to atomizing the fuel, the small, carefully controlled size of the nozzle exit orifice serves to control burner firing rate. Burners of this type are currently available at firing rates over 0.5 gph (21 kW). Nozzles have been made for lower firing rates but experience has shown that such nozzles suffer rapid fouling of the small passages required, leading to bad spray patterns and poor combustion performance. Two factors contribute to this fouling. The first is fuel system dirt which might be controlled through better filtration. The second is coke formation on internal passages occurring after normal burner shutdowns when the nozzle is heated by radiation from the combustion chamber. This period after shutdown is more severe than while the burner is actually firing During the on period there is a cooling effect of flowing oil and the combustion air flow over the nozzle. At shutdown, oil remaining in the nozzle line is heated from the still-hot refractory and hard coke can form.

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The pressure-atomized, retention head burner has an excellent reputation for reliability and efficiency. While it is only correct to discuss the efficiency of complete heating systems rather than the efficiency of the burner alone, the burner has a very strong influence on system efficiency in several important ways. To achieve high efficiency, the burner should be capable of operating with a minimum of excess air. Smoke production during warm-up and in steady state are the factors which set the lower limit on excess air. Most modern pressure-atomized burners can operate at excess air levels as low as 15% at a firing rate of 1 gph (41 kW), under good conditions (Krajewski et al. 1990). At low firing rates, higher excess air levels are required. A second way in which burners can influence system efficiency relates to fouling of heat exchanger surfaces and degradation of efficiency over time. Burners which are operating very badly, possibly because of a fouled nozzle for example, may produce high smoke levels leading to rapid coating of heat exchanger surfaces with carbonaceous soot. In more normal cases, where the burner continues to operate smoke-free the fouling rates will be lower. One field study concluded that the average efficiency degradation rate is 2% per year (Kelly et al. 1984). Studies at Brookhaven National Laboratory (BNL) have shown that a very important part of the normal fouling deposit is iron sulfate scale resulting from the deposition of sulfuric acid from the flue gas onto the heat exchanger surfaces. The amount of sulfuric acid which is produced in a flame is dependent upon the burner excess air level. Acid production and scaling rate can be controlled by using burners which can operate at very low excess air levels (Celebi et al. 1990; Butcher, Celebi and Wei 1992; Butcher and Celebi; 1993).

Another way in which burners can influence heating system efficiency is through off-cycle losses. After the burner has shut off, the system continues to lose heat up the chimney. This heat loss rate depends upon the rate of air flow through the unit which, in turn, depends upon the burner design. A burner which has high fan pressure also has small open passages that allow lower off cycle air flow rates.

The objective of the effort described in this paper is the development of an advanced, air-atomized burner which can provide new capabilities not currently available with pressure atomized, retention head burners. Specifically this includes:

- ability to operate at firing rates as low as 0.25 gph (10 kW);
- ability to operate with very low (5%) excess air levels (14%+ CO_2) for high steady state efficiency and to minimize formation of sulfuric acid and iron sulfate fouling;
- low emissions of smoke, CO and NO_x at these excess air levels;
- potential for modulation - either stage firing or continuous modulation.

In addition, of course, any such advanced burner must have production costs which would be sufficiently attractive to allow commercialization.

In the past a number of very interesting designs for achieving some or all of the objectives listed above have been developed to varying degrees. Air atomization, blue flame (recirculating), and prevaporizing burners have received attention. An excellent review of prior work in this area was published in 1980 (Locklin and Hazard 1980). Some of the more recent work in advanced burners has been described in the proceedings of the annual BNL Oil Heat Conferences. In 1990, a study was completed in which the emissions performance of conventional and advanced burners were compared (Krajewski et al. 1990). This study included air atomization and prevaporizing burners. General options for atomizers for advanced burners were also reviewed (Krishna et al. 1987). Reasons why none of these advanced burners are currently available commercially vary but generally include: high cost, poor reliability, excessive complexity (difficult to service), and others.

In all residential air-atomized burner concepts which have been developed, a small compressor was used to provide a small flow of air at 5 to 20 psi (34 to 138 kPa) to the nozzle for atomization. A conventional fan was also included to provide the remainder of the air needed to complete combustion. This secondary air is delivered at much lower pressure, about 1 inch of water (.25 kPa).

The atomizer used in the burner described below is a low-pressure, high volume nozzle. It can achieve good atomization with air pressures ranging from 6 to 12 inches of water (1.5 to 3. kPa). The volume of air used for atomization is considerably greater than with high pressure atomizers. Depending upon firing rate, from 15 to 40% of the total combustion air is used for atomization. From a burner design perspective, this approach carries an inherent advantage - all of the air required for both atomization and combustion can be provided from a single fan.

The atomizer used in this burner is based on a nozzle originally developed under a project to heat air and clean a catalytic filter used to reduce particulate concentration in diesel engine exhaust (Tuteja et al. 1992). Figure 1 provides a simple illustration of the nozzle (side cross section). Air at pressures of 6 to 12 inches of water (1.5 to 3. kPa) enters the back. Most of the air passes through the outer swirler and spins out through the main exit orifice. A smaller amount passes radially inward through four, small offset holes ("A" in Figure 1.) providing co-swirling air around the pintle. Fuel entering at the centerline flows radially out through three small holes near the pintle tip where the swirling air distributes and swirls the oil, filming it as it leaves the inner orifice ("B" in Figure 1). The two swirling air flows accelerate as they converge at the exit orifice, shearing the sheets and ligaments of fuel into a conical spray.

PROTOTYPE BURNER DEVELOPMENT

Figure 2. is a very simple illustration of the way in which the burner head has been developed for the nozzle. While not correct in detail, this sketch shows how all of the air from a single plenum at the back of the burner is divided into three parts: atomizing air entering the set of holes in the back end of the nozzle body and exiting the nozzle at point 1; secondary air which passes through a set of small holes in a metering plate (which surrounds the nozzle body) and then enters the flame zone through slots, 2, in the retention plate; and tertiary air which enters the flame zone through a small annular passage, 3. The head can be moved backward and forward, increasing and decreasing the tertiary air flow for adjustments in firing rate or the excess air level. The flame is surrounded by a metal flame tube (not shown in Figure 2) which improves flame retention and cold start performance, improves combustion in some cold-wall applications, and controls gas recirculation rates.

The complete system developed for the first burner prototype is illustrated in Figure 3. Air at the required pressure is provided by a 5 inch (12.7 cm) diameter plastic blower driven by a brushless DC motor at high speed. At the nozzle, the required fuel pressure is less than 1 psig (6.9 kPa). An electric solenoid fuel pump is used in combination with a bypass type pressure regulator (typically set at 7.5 psig (53 kPa)) and a metering orifice to deliver the required amount of fuel to the nozzle. The control being used has interrupted ignition and provides programmable pre- and post purge periods.

Combustion tests with the prototype burner have been done in a wide variety of equipment in the BNL lab including furnaces, water heaters, cast iron boilers, and steel boilers (Butcher, Celebi, and Fisher 1992). While this testing has been done over the firing rate range 0.25 to 1.0 gph (10.3 to 41 kW), most of the emphasis has been on rates less than 0.5 gph (21 kW). For example Figures 4 and 5 provide a comparison of the smoke and CO / excess air relationship with a conventional retention head burner and the Fan-Atomized Burner. These tests were done in a steel boiler with a horizontal, cylindrical combustion chamber.

NO_X emissions with the Fan-Atomized Burner tend to be somewhat lower than with a retention head burner at the same firing rate. When operated at still lower firing rates, the Fan-Atomized Burner will produce much lower NO_X emissions. Figure 6 shows the effect of firing rate on NO_X in the same steel boiler discussed above. These tests were all conducted with the Fan-Atomized Burner prototype operating at 12% excess air. For comparison, pressure atomized, retention head burners produce NOx levels ranging from 70 to 110 ppm in similar applications.

While performance of the first burner system prototype was found to be very good, concerns were raised about its commercial potential due to the use of components which are unconventional in the heating industry. This specifically refers to the fan and fuel pump. For this reason a second prototype was planned to include conventional components to the greatest degree possible. The greatest challenge in doing this is the fan - conventional oil burner fans develop maximum static pressures of only about 3 inches of water (0.75 kPa). Combustion studies indicated that acceptable burner performance could be achieved with air pressures as low as about 4 inches of water (1 kPa). A nearly conventional, squirrel-cage fan suitable for use with an oil burner was developed which produced a pressure of 6 inches of water (1.5 kPa) under firing conditions. This fan is driven by a 3450 rpm AC motor which can then also drive a fuel pump as in a conventional burner. The fuel pump used with the second prototype is a modification of a standard burner pump. The primary difference is that its internal pressure regulator can operate at the much lower pressure. This pump provides the same dry lift and reliability characteristics expected by the industry. The burner uses conventional safety controls and interrupted ignition. Performance testing has been done with this second burner prototype over the firing rate range 0.25 to 1.0 gph (10.3 to 41 kW) and excellent performance at CO_2 levels over 14% are achieved.

FIELD TESTS

Field trials with the Fan-Atomized Burner prototype have been conducted during the 1994/1995 and 1995/1996 heating seasons in one home on Long Island. At this site, the existing boiler is a steel, dry base boiler fired with a conventional retention head burner running at a firing rate of 0.7 gph (28.7 kW). Hot water is provided by a "tankless" coil in the boiler. For the field test, a new boiler was added at the site temporarily and the piping and controls configured such that either boiler could be operated. Instrumentation was installed to monitor system temperatures, fuel use, and heat delivered to both the baseboards and domestic hot water. The new boiler was planned to take full advantage of the capabilities of the Fan-Atomized burner. It is a steel, positive pressure boiler, side wall vented without a draft inducer. The control on the Fan-Atomized Burner was programmed for a 15 second pre-purge and 10 second post-purge. After completion of a heat call, extra heat stored in the boiler is purged into the heated space and the boiler may go fully cold between cycles. A separate, well insulated, 40 gallon (.15 m^3) hot water tank is used with the test system and this is treated as a priority zone.

Testing was done at several different firing rates although the most extensive testing was done at 0.35 gph (14.4 kW). At this input rate, the test system had no difficulty in meeting the heating and domestic hot water demand with outdoor temperatures as low as 7 F (-14 C). This is the lowest observed outdoor temperature during the test period and is the 99% design point for the location (ASHRAE 1993). At the lowest outdoor temperature conditions for which field testing was done, the burner was on about 90% of the time. Under similar outdoor temperatures, the Fan-Atomized Burner test system has an on/off cycling rate about 83% less than the baseline system. This is due, in part, to the capacity of the hydronic distribution system. At burner firing rates above about 0.45 gph (18.5 kW) the energy input exceeds the capacity of the system to deliver heat to the house and the system cycles on the high temperature limit control (Litzke et al. 1996).

At 0.35 gph (14.4 kW), and 13.5% CO2, the steady state gas temperature leaving the boiler is about 300 F (150 C), giving a steady state efficiency (based on stack loss) of 88%. Figure 7 provides a comparison of the efficiency/load curves of the old system and the test system with the Fan-Atomized Burner based on heat balance. Burner noise was not found to be objectionable in the field. Based on occupant observations the test burner system was quieter than the older, retention head burner system.

STANDARDIZED EFFICIENCY TESTING

In addition to the field testing, the FAB's capabilities have been examined using standardized test procedures specified either by the U.S. Department of Energy, where available, or by ASHRAE/ANSI where federal standards have not yet been implemented. The tests were done to identify sources of FAB performance advantages, indicating how much of the improvement is due to being able to operate reliably at low firing rates and how much is due to other design advantages. Comparative performances were measured for FAB's and retention head burners in water heating, space heating and combined appliance applications.

Equipment and Procedures

In each of the test procedures referenced below, the test arrangement and procedures are fully defined. In each case the boiler is tested under simulated field conditions. Because these test beds are fully defined in the standards, diagrams are not included here.

The temperature of the exhaust gas was measured by a thermocouple grid in the insulated flue pipe. Draft on the test units was imposed by a controlled induced-draft fan arrangement. The data taking is largely automated. Where spatial averages were called for (in the flue, stack and water tanks), grids and ladders of thermocouples wired in parallel with leads of equal length were installed. Water flows were measured with a target meter calibrated against the weighed water in situ. Fuel consumption was constantly monitored by a digital balance. Both the datalogger and the balance were interfaced to a desktop computer, where a specially written Basic language program took the data specified by the standard, turned flows on and off (using digital I/O) in accordance with specified procedures, and maintained operating parameters (e.g. input water temperature) within specified ranges. Total water processed (in water heating applications) was measured on a large digital scale; these data were read by the experimenter and typed into the Basic control program on cue. The program also stored data to disk in real time, so at the end of given experiment a complete data file was available for analysis. The analysis was carried out in spreadsheets constructed in accordance with the specifications for calculations in the standards.

Water Heating

Efficiency studies were completed with a center-flue water heater fired with a conventional retention head burner (baseline) and with the Fan-Atomized Burner. All tests were done in accordance with standard procedures for oil-fired water heaters (US DOE, 1995-1).

Table 1, below, lists the most important performance parameters as measured and also as listed for this appliance. In the tests reported here, we only approximated the manufacturer's specified conditions. The retention head burner, used at the rated firing rate (.75 gph (30.8 kW)) was not the burner listed by the manufacturer. In the baseline tests burner excess air was set at 50%. In tests with the FAB the firing rate was 0.37 gph (15.2 kW) and excess air was set at 10%.

The retention head burner did not perform up to its listed specifications in our tests. We expect that the differences are due to the differences in the burners used and high excess air in the case of our retention head burner tests. Comparison of test results for the retention head burner and the FAB indicate that while the low firing rate has reduced the first hour capacity by some 36%, it has increased efficiency so as to offer more than 10% fuel savings. These results clearly indicate the efficiency advantages provided by the FAB's reliable low firing rate.

Annual Fuel Utilization Efficiency (AFUE)

The tests followed the current standards for the energy consumption of furnaces (US DOE, 1995-2). For the single firing rate boilers we are currently examining, this standard is identical to the current ASHRAE standard (ASHRAE 1993). This Annual Fuel Utilization Efficiency (AFUE) standard is based on the measurement and stoichiometric calculation of thermal losses up the flue and estimates of coincident infiltration and additional stack losses to determine steady state efficiency. AFUE also involves tests of the cool-down and heat-up performance of the system, including a "tracer gas" measurement of the amount of air drawn through the shut-down burner by residual draft. These data allow calculation of likely cycling losses, which are combined with the steady state efficiency to give the AFUE.

The FAB and a conventional retention head burner were tested in two different boilers at a variety of firing rates. The first boiler had a hot (semi-insulated) combustion chamber surrounded by a steel water jacket which offered substantial heat transfer surface to the hot gases, and was oversized for the low firing rates obtained with the FAB when judged by current practice. The results are summarized in Table 2, below. The four individual losses listed below the Steady State Efficiency give the AFUE when combined with the latent heat loss of the fuel (L_{LA} = 6.5%). The "L" refers to "loss", "S" to "Sensible" (i.e., up the stack), "I" to "infiltration (i.e. make-up air), and "ON" and "OFF" to on-cycle and off-cycle losses respectively.

The primary source of the FAB's higher efficiency is its ability to operate reliably at low firing rates, permitting more effective use of heat exchanger surface, which appears as lower on-cycle sensible losses. Another advantage is apparent in the entries for L_{SOFF}, where the small air intake orifices have reduced the off-cycle sensible heat losses as well. For both FAB tests, air flow up the flue after burner shut-down was about 0.5 cfm (0.85 m^3/hour), while for the retention head burner it was 3.4 cfm (5.8 m^3/hour).

The second boiler tested was a smaller cast iron unit, which served in the combined appliance tests discussed below as well as in AFUE tests. The results of the AFUE tests are summarized in Table 3. The increase in steady state efficiency when the retention head burner is fired with the smaller nozzle shows the gain obtained by lowering the firing rate in the cast iron boiler, although these gains are hard to realize in the field due to the unreliable behavior of pressure-atomizing burners at these low firing rates. The FAB can reliably deliver this efficiency improvement and more, due to the FAB's lower average sensible heat losses.

It should be noted that our test of this boiler, carried out with the factory-installed burner, gave an AFUE of 83.3%, while the published tables (GAMA 1995) give an AFUE of 83.5%, indicating that our procedures are in good agreement with the standard.

Combined Appliance Efficiency Test (CAET)

CAET's have also been completed for all three of the above systems, making use of the tankless coil included in the cast iron boiler, and with no storage capability. The results are summarized in Table 4, and are similar to those for the hot water heater described earlier. In our experience, the first hour draw is not as repeatable as the efficiency measurements, due to an element of chance in determination of the "base" temperature against which the acceptable drop is measured.

The "energy factor" indicates the expected efficiency during the summer, when the entire burner/boiler system is being used only to supply hot water. The winter efficiency is slightly higher than the AFUE (since the increased use due to hot water demand leads to a slight increment in efficiency), and this is averaged with the energy factor to give the "Combined Annual Efficiency" values. Again, comparison of the two results for the retention head burner indicate the value of the FAB's reliable lower firing rates, while comparison of the FAB to the low-firing rate retention head burner indicates the value of its lower sensible heat loss.

TWO-STAGE BURNER PROTOTYPE

The basic single stage low firing rate FAB burner can be altered to accomplish two-stage or "high/low" firing through an adjustment of both the air side and fuel side flow rates. By adjusting both, the excess air level is low at both firing rates. A prototype burner of this type has been built and tested. High and low rates of fuel flow are achieved simply by using two solenoid valves, each with a fuel flow orifice. At "high fire" both are open and at low fire, only one. The air flow is adjusted for firing rate by changing the position of the burner head. Referring to Figure 2, For high fire the fuel line, nozzle, and other head components are moved away from the tip, increasing the tertiary air flow area. This is accomplished using a direct current, latching solenoid.

The present design offers a single selectable firing rate through the manual actuation of a switch to either high-fire or low-fire conditions. This switch is a "double pole, double throw" momentary design with a spring-loaded, center-off position. Actuation time for the controlling circuit is less than 0.1 seconds so that power drawn for the manual actuation is assumed to be negligible.

The momentary switch closure to the high-fire position does two things simultaneously: 1) it actuates a latching solenoid which pulls the burner head assembly toward the rear of the burner and increases a restoring force provided by a spring. This selected position has the effect of increasing the tertiary air flow. The solenoid locks in the high-fire position through the use of a permanent magnet assembly built into the actuator.; 2) it actuates a pair of solenoid valves which provide sufficient fuel flow through two orifices to satisfy the high-fire the excess-air requirement.

Positioning the momentary switch to select the low-fire position does two things simultaneously: 1) it reverses the solenoid field momentarily defeating the permanent magnet and allows the spring restoring force to reposition the solenoid armature and burner head to the low-fire position. This selected position has the effect of decreasing the tertiary air flow.; 2) one of the fuel side solenoid valves closes and provides sufficient fuel flow through a single orifice to satisfy the low-fire excess-air requirement.

A two-stage version burner would provide most of the high efficiency advantages of low firing rates, while providing capacity for infrequent, high load conditions. The results of AFUE tests presented in Table 2 can be used to illustrate this point. For this example a two stage burner is assumed , with the high input rate at 0.79 gph (32.4 kW) and an AFUE of 85.4% as in column 2 of this table and the low input at 0.44 gph (18.0 kW) and AFUE of 89.5% (column 3). The AFUE calculation procedure for a two stage system (DOE 1995-1) leads to 95% usage at low input and only 5% at the high input rate for a 60,000 Btu/hr (17.6 kW) building design heat requirement over the year. The AFUE for the two-stage system is 89.3%, very close to the low input rating.

CONCLUSIONS

A new concept for a residential oil burner has been presented. The low pressure, air atomized burner concept offers improved efficiency, when fired into current boilers and water heaters, and lower firing rates than conventional, pressure atomized burners. The concept has strong potential for two-stage firing which can offer both high efficiency and capacity for intermittent high load conditions.

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