TRANSIENT EMISSIONS ASSOCIATED WITH VARIOUS FURNACE CYCLIC PATTERNS IN RESIDENTIAL OIL COMBUSTION - A LABORATORY STUDY

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INTRODUCTION

Environmental considerations dictate that combustion processes increase energy efficiency, reduce pollutant emissions from fossil fuels and utilises alternate fuels that generate fewer particulates and volatile organics. These considerations will receive greater attention than the operational costs as the environmental awareness of a concerned public increases. All combustion processes are potential air pollution sources and most of the major fuel consuming units are covered by government regulations, the residential heating appliance being one of the few exceptions. In Canada, with its cold winter climate, energy in the form of electricity and heating fuel for domestic requirement makes up for about one-fifth of the total national energy consumption. Energy conservation in the residential sector is encouraged nationally and an average homeowner sees its direct effects as immediate dollar savings. However, there is a need to increase the public awareness on the environmental impact of reduced energy consumption since it is not as evident as in cost reduction.

The Combustion and Carbonization Laboratory, a federal research facility long associated with research programs to promote efficient use of energy, provides technical information including publications on conservation strategies and pollution emissions in residential oil heating (1, 2). Data from field studies revealed that the most effective strategies for both fuel saving and emission reduction are the use of a high efficiency low excess air burner, lowering the overnight thermostat setting significantly, and by reducing the burner firing rate. As for reduction of seasonal emissions of carbon monoxide and particulates, a combined strategy of reduced fuel consumption and reduced cycling frequency was suggested. The authors observed that these emissions were contributed equally by cyclic emissions and steady-state emissions at combustion air levels giving steady-state smoke numbers close to one.

Keywords: cyclic combustion, emissions, residential heating

A similar study by other researchers reported that particulates, carbon monoxide, and hydrocarbons decrease in concentration as the excess air level increases and that hydrocarbons tend to increase once excess air level reaches a certain level and beyond (3). An apparent linear correlation between particulate emissions and final boiling point of the fuel at low excess air conditions was also suggested. The present study focuses on laboratory measurements of startup transient emission levels at different burner on/off cyclic operations. The purpose is to determine the effect of burner cyclic pattern, especially "off" period on emission concentrations. This work is part of the ongoing research program on fuel quality and combustion characteristics of middle distillates at the Combustion and Carbonization Research Laboratory.

MATERIALS AND METHODS

Fuel Types and Properties

Eight specific fuels with different characteristics (Table 1) were selected for this work. Fuels N, Q, HH, and FF are commercial No. 2 heating fuels purchased locally. Three other fuels (OO, CC, PP, EE) were contributed by various Canadian oil companies. The origin of crudes and the refinery processes utilized to produce the fuels vary depending on the company and location. They were specially blended to obtain a wide range of properties especially varying aromatic concentrations. Fuel FF was used in combustion tests with variable cyclic pattern and the rest were used in simulation tests for reduced overnight thermostat cut-back (lowering of setting) situations.

Combustion Experiments

All combustion experiments were carried out using the procedure and facilities developed at the Combustion and Carbonization Research Laboratory (4). The schematic of the experimental facilities is shown in Figure 1. The experimental procedure can simulate the actual usage pattern of residential oil heating in Canadian homes. A typical experimental run starts with an initial burner startup (cold start) lasting one hour (steady state), immediately followed by five consecutive cyclic operations with selected on/off time pattern. Flue gas emissions and temperatures at specified locations of the test rig are continuously monitored over the entire run. The following experimental equipment and operating conditions were used.

Fuel temperature:	15 $\pm$ 2 °C
Nozzle oil temperature:	[1]7 - 20 °C for cold start
Fuel pump pressure:	100 psi
Oil nozzle:	0.65 US gph, 80° spray angle
Combustion air:	Set to obtain a No 2 smoke at steady-state with Bacharach tester for each fuel

Cold air return temp:	15 ± 1 °C
Burner:	Beckett domestic gun type burner with Areo AFC-2 flame retention head
Furnace:	Forced air type. Brock model LO-1M, 74,000-120,000 Btu/h, with concentric tube type heat exchanger.
Furnace draft:	1 mm (0.04 in) of water column

Equipment for Emission Monitoring

The oxygen analyzer was a paramagnetic type instrument while the carbon dioxide and carbon monoxide analyzers used the infrared detection principle. Nitrogen oxides in the flue gas were measured by a chemiluminescent type instrument. Particulates were measured manually with a Bacharach smoke tester and continuously with a Celesco model 107 in-line smoke opacity meter. Temperature of the oil in the nozzle line was measured continuously using a "K" type thermocouple inserted through a hole in the nozzle adaptor located as close as possible to the nozzle.

The burner cold-start operation was simulated in the laboratory by cooling the appliance, especially burner and combustion chamber by a blast of chilled air until they attained temperatures comparable to those of a residential basement environment. Based on the actual readings from homes, oil temperature in the nozzle line was lowered to 17-20 °C.

RESULTS AND DISCUSSION

No two homes will have the same appliance on/off cyclic operation pattern since it varies depending on numerous factors. The appliance type and condition, level of home insulation, climate, location, user comfort level and life style, thermostat anticipator setting, and overnight temperature setting all determine the operation mode of a residential burner. The cyclic pattern strategy described in Table 1 attempts to simulate some of the possible situations but by no means represents the numerous real life conditions in homes. These patterns are selected to reflect the usage pattern of most Canadian homes where lowering the thermostat setting before retiring at night is the accepted practice for energy conservation.

The degree of severity in overnight thermostat cut-back, however, controls the length of the burner cycles and consequently the burner performance at the cold-temperature conditions. The performance may be adversely affected in the case of fuels with slightly lower grade specifications and of high aromatics as have been predicted for marketing, before the fall of oil prices in 86. Four special blends were selected to represent this senerio.

Transient emissions from cyclic combustion of a No. 2 fuel at variable on/off cyclic patterns

As reported in the literature, gaseous and particulate emissions of a residential burner are higher at transient startups and shutdowns than steady-state conditions. The peaking of emissions at startup is due to the cold temperature conditions, mainly low fuel volatility leading to a poor fuel/air mixing, before the combustion zone temperature rises. Immediately upon shutdown, incomplete combustion products result due to an excess fuel condition created by the high pressure oil pump and lack of combustion air supply. These emission peaks are difficult to reproduce by a burner and concentrations between five consecutive cycles show variations with a relative standard deviation of 5% to 20%. The reproducibility of emission data from controlled cyclic operations is much better for typical commercial fuels than those of lower grade fuels.

Data in Table 3 show particulate and gaseous emissions at different transient startup conditions. Each value represents the average of data from a minimum of three experimental runs, each run having five consecutive cycles. Opacity % reported in Table 3 represents the average maximum opacity reading at the peak of transient particulate emissions as recorded by the smoke opacity meter. The reproducibility of opacity, calculated as relative standard deviation, between each run ranges from 7% to 26%. Despite this moderate error margin, there appears to be a gradual trend to increasing particulate levels with the increase in burner cooling-down time. A noticeable increase in particulate emissions was noted after a 7 to 10 hours burner "off" period (simulation of an extreme overnight thermostat cut-back condition). A gradual decrease in the oil temperature in the nozzle line was noted as the burner off period increased. This cooling- down process is dependent of the combustion chamber design among other variables. Similar variable cyclic tests in a different appliance may or may not find the same observations. Data indicate that severe thermostat cut-back could increase pollution emissions from a residential oil burning unit. However, this emission increase is compensated, by several magnitudes, by the total emission reduction resulted from the long burner "off" period.

These combustion tests were carried out using Fuel FF under identical steady-state particulate concentrations of Bacharach smoke number 2. This condition provided an steady-state efficiency of 84% and an excess air of 36% (equivalence ratio of about 1.4). During a one hour steady-state run before cycling, the CO emissions were between approximately 30 ppm and no detectable hydrocarbons were recorded. CO and hydrocarbon emissions at transient startups are significantly higher than steady-state levels. They appear to be similar in magnitude for all variable cyclic operations. Nitrogen oxides concentrations are consistent in all steady-state and transient emissions.

Transient emissions from cold-start and cyclic combustion of different distillate oils

The difference in transient particulate emissions from cold-start and cyclic combustion experiments using different fuels is seen in Table 4. Data indicate that cold-start particulates are higher than cyclic emissions for all fuels. This could be mainly due to the combustion temperature differential between the two operations. The actual thermocouple reading recorded during an experimental run showed that the oil temperature in the nozzle line was between 17-21 °C at cold-start and between 35-65 °C during cyclic operations following a one hour steady-state run. The significant effect of oil temperature at ignition on particulate emissions of residential burners was reported elsewhere (5). Favourable warm temperatures of the oil and combustion zone allows efficient burner ignition and reduced incomplete combustion products.

Data in Table 4 also indicate that, using the same burner, higher cold-start smoke emissions resulted from fuels with higher aromatics. Cyclic transients of the fuels are comparable (Fig.2). Smoke opacity, resulting mainly from soot in the flue gas, is an indicative combustion parameter since other incomplete combustion products exhibit similar emission trends. Although the fuel aromatics are not included in current specifications, volumetric concentrations of aromatics of No. 2 heating fuels fall within 20 to 40%. Special blends have aromatics concentrations higher than 40 %. 90% boiling point of the fuels appear to be proportioal to aromatics. Data suggests that cold-start emissions may be of concern if the fuel aromatics reaches about a 60 % level. The strong influence of fuel viscosity and aromatics on burner performance have been reported previously by the author (6). It was shown that off-spec, low quality fuels generate higher emissions of incomplete combustion products such as particulates, carbon monoxides and hydrocarbons than normal fuels. A complex relationship among fuel properties such as aromatics, viscosity, boiling point range, carbon residue, and gravity influences combustion emissions. This paper is limited to the scope of burner performance at various cyclic patterns.

The following conclusions can be drawn from this study;

1. Transient emissions from varying burner on/off cyclic patterns show a slight increasing trend of particulate emissions as the burner cooling-down period increases.
2. Cold-start ignition after a burner cooling-down period of more than 7 hours, simulating a severe thermostat cut back situation generates higher emissions than cyclic operation.
3. Cold-start transient emissions increase with increasing fuel aromatics and final boiling point but cyclic emissions are less affected by fuel properties.

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Table 1. Basic Properties of Fuels

Fuel	Density Kg/L @ 15°C	Viscosity c St @ 38°C	Aromatics Vol %	90% BP °C	Calorific Value MJ/kg
N	0.845	2.09	30.3	322	44.3
Q	0.846	2.59	30.6	325	45.5
FF	0.855	2.52	31.4	311	44.5
HH	0.861	2.82	39.2	308	45.1
CC	0.902	2.70	54.2	315	43.9
OO	0.914	2.56	55.2	304	43.7
PP	0.916	2.61	60.0	327	43.2
EE	0.912	2.90	68.0	368	43.2

Table 2. Laboratory Furnace Cyclic Operation Pattern to Simulate Various Periods of a Heating Season

ON time (m)	OFF time (m)	ON/OFF ratio	Approximate period
5	15	0.33	Fall and spring months
5	10	0.5	Fall and spring months
5	5	1.0	Most of winter days
10	10	1.0	Most of winter days
3.8	13.3	0.29	ASHRAE 103 standard average
10	30	0.33	At lower thermostat settings
10	overnight		Under extreme thermostat cut-back conditions

ASHRAE is American Society of Heating, Refregeration & Air-Conditioning Engineers

Table 3. Maximum Transient Emissions Resulting from Different Cyclic Combustion Processes of Fuel FF

on/off time (m)	Opacity (%) & BSN[a]	Carbon monoxides (ppm)	Hydrocarbons (ppmc)	Nitrogen oxides (ppm)
10/5	1.1 (6)	235	14	75
10/10	1.2 (6)	250	20	73
5/5	1.2 (6)	260	15	73
5/10	2.2 (7)	265	30	75
5/15	2.6 (8)	190	20	76
3.8/13.5	2.1 (8)	330	25	72
10/60	2.9 (8)	325	23	75
overnight	3.1 (9)	360	32	72

[a] BSN represents Bacharach smoke number

Table 4. Startup Transient Particulate Emissions from Different Fuels

Fuel	Maximum Cold-start Opacity %	Maximum Cyclic startup Opacity %
N	1.7	0.2
Q	1.6	0.4
FF	3.1	1.2
HH	1.4	0.9
CC	4.7	2.3
OO	2.8	1.3
PP	3.9	1.8
EE	26	2.9

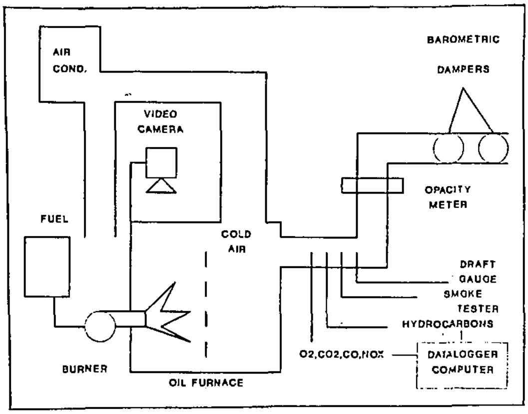

Figure 1. Schematic of equipment for combustion experiments.

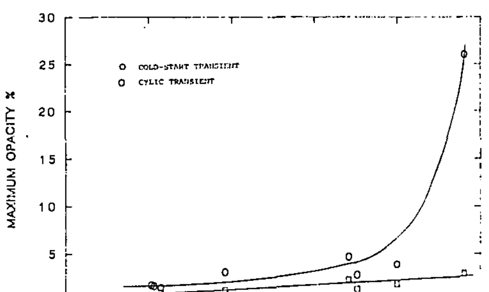

Figure 2. Startup transient particulate emissions from different fuels.