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ENERGY CONSERVATION AND EMISSIONS FROM TWO RESIDENTIAL FURNACES USING AN EMULSIFIED WATER-IN-OIL FUEL

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By

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Abstract

As part of a continuing study of energy conservation strategies applicable to residential heating systems, the Canadian Combustion Research Laboratory (CCRL) evaluated the performance and emission characteristics of two units when fired with emulsified water-in-oil fuel.

A warm-air furnace and a hot-water heater were fired with No. 2 fuel oil containing up to 60% water by volume. For comparative purposes each unit, which originally had similar cast-iron head burners, was fitted with a retention-head burner known to give superior performance. The use of emulsions increased efficiency only marginally: less than 2.6% with the cast-iron head burner and less than 0.3% with the retention head, both at low water-in-oil contents (0.5 - 5% w/o). When both units were operated on No. 2 fuel oil alone, the retention head increased efficiency by about 6.5% when compared with the cast-iron head.

In general, CO emissions increased and NO emissions decreased as the water content of the fuel was increased. The cast-iron head burner gave a peak NO emission at about 5% w/o indicating optimum conditions. Although the retention head did not produce such a peak, its improved turbulent mixing generally gave NO levels about double those produced by the cast-iron head. The retention head allows operation closer to the stoichiometric level for the same smoke emission; the same cannot be said of emulsified water-in-oil fuels.

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Introduction

The role of water in fuel-oil combustion has a long history dating back to the development of the steam atomized burner. During the past thirty years there have been periodic resurgences of interest in emulsified water-in-oil fuels but only in recent year — because of stricter environmental regulations and rapidly increasing oil prices — has the suggestion been made that such emulsions will reduce pollutant emmissions and oil consumption when used under optimum conditions in combustion systems. One of the postulated mechanisms for these benefits is the so-called "micro-explosion",[1] in which better atomization is caused by rapid water-to-steam evaporation inside the oil droplet, leading to improved combustion performance and reduced emissions of some pollutants.

Many devices are now available that provide mechanically stablized emulsions for large commercial and industrial applications. These devices, which employ high pressure mechanical, low pressure mechanical or ultrasonic energy to provide stable emulsions, are clearly uneconomical in residential heating applications. However, as part of the U.S. Environmental Protection Agency in-house test program, Hall et al[2] have studied the effect of mechanically produced emulsions on pollutant emissions from a residential warm-air furnace and on the combustion efficiency of the unit. They showed that whilst there was little change in efficiency when operating with emulsions of up to 32% w/o there were reductions of NO, particulate mass and smoke emissions. There was no change in CO or hydrocarbon emissions.

In 1976 as part of the Energy Research Program of the Canada Centre for Mineral and Energy Technology (CANMET), the Canadian Combustion Research Laboratory (CCRL) began an evaluation of water-in-oil emulsions as an energy conservation strategy in residential heating. Two typical furnaces — a warm-air furnace and a hot-water boiler — were selected for testing using a chemically stablized, mechanically produced emulsion. They were fired with No. 2 fuel oil and with emulsions containing, in some cases, up to 60% by volume of water. Other conservation strategies such as nozzle size reduction and burner head modification were included in the test program for comparative purposes.

Test Equipment

Both units tested were considered typical and had been on the market for some years in Canada; therefore, neither incorporated any recent modifications to reduce oil consumption such as extended heat transfer surfaces or improved burner design. Each had a similar burner equipped with a cast-iron head which is ineffective in imparting turbulence and swirl to the combustion air. For comparative purposes each burner was modified after testing, and the head was replaced by a retention head, a more efficient turbulence generator which typically improves furnace efficiency by about 10%[3,4]. It was felt that, since the water in the fuel appears to improve combustion through better atomization and mixing, the less efficient cast-iron head should show the greater improvement.

Hot-Water Heater

The hot-water heater tested had a maximum rated output of 169,000 Btu/hr at a firing rate of 1.5 US gph. In the test program a firing rate of 1.0 US gph was selected for both the cast-iron head and the retention-head burner configurations. To maintain a steady load on the heater, the output hot water was passed through a fan-cooled heat exchanger and the water returned to the unit at 110°F.

Warm-Air Furnace

The warm-air furnace tested had a maximum rated output of 112,000 Btu/hr at a firing rate of 1.0 US gph. In the test program, to determine any possible interaction of emulsified fuels and nozzle reduction as energy conservation strategies, 0.75 and 1.0 US gph firing rates were used in conjunction with both the cast-iron head and retention-head burner configurations. To maintain steady-running operation the thermostat control was by-passed.

Emulsified Fuel Supply

Preparation of Emulsions. The reference fuel for the test program was No. 2 fuel oil of specific gravity 0.85 and calorific value 19,600 Btu/lb, typically sold for residential heating in Canada. Water-in-oil emulsions of varying water content were mixed volmetrically for each test in a 12 U.S. gallon reservoir. An auxiliary oil pump installed in a closed loop was used to circulate the water-in-oil mixture and provide some dispersion of the two phases. This alone was not sufficient to form a stable emulsion; consequently about 4% of a commercial w/o emulsifier was added to the oil phase before adding water. This amount cf emulsifier in the emulsion is expensive, but is required if low w/o content emulsions (1 - 10% w/o) are to remain dispersed for more than a few minutes without the auxiliary pump in operation. A microscopic examination of several emulsions in the ranges of w/o content used showed that the water was typically dispersed in the 0.5 to 10 μm size range.

The oil supply to each unit was arranged so that either No. 2 fuel oil from a 300 U.S. gallon supply tank or emulsion from the small tank could be used. This was necessary for reference tests on No. 2 fuel oil; also, because emulsions of greater than 25% w/o gave rise to ignition difficulties, the burner had to be started on No. 2 fuel oil before changing to the emulsion.

The Pumping of Emulsions. From the conservation viewpoint, it is important to ascertain how much oil is actually consumed when burning emulsions of varying water content. Because the pumping characteristics (viscosities) of the emulsions were expected to change with water content, measured flowrates could be correlated with fuel oil content and thereby used to determine actual fuel oil consumption.

Table I shows emulsion and No. 2 fuel oil flowrates at each nominal firing rate and for various selected levels of water content. It is interesting to note that the nominal firing rate of each nozzle was about 15% higher than that measured for No. 2 fuel oil supplied at a pressure of 100 psig. The reduction of oil consumption at 50% w/o was about 40% for both nominal firing rates.

Monitoring of Combustion Performance and Emissions

The main emissions from residential heating are soot, nitric oxide and carbon monoxide[3]. To some extent carbon monoxide and soot are indicators of combustion performance since they represent incomplete particulate emissions, is also an indicator of combustion performance because the particulates typically contain 99% unburnt carbon or soot. Combustion performance was monitored by continuously measuring O_2, CO_2 and furnace exit temperature;

emissions were monitored by continuously (No. 1 Smoke) the smoke number was measured at frequent intervals. The instrumentation used was:

Parameter	Instruments
Oxygen (O_2)	Paramagnetic
Carbon Dioxide (CO_2)	N.D.I.R.
Carbon Monoxide (CO)	N.D.I.R.
Nitric Oxide (NO)	Chemiluminescent
Smoke Number	Bacharach Smoke Tester
Flue Gas Temperature (°F)	Thermocouple and Temperature Indicator

Experimental Program and Results

The test program on the two units was planned mainly to evaluate the potential of w/o emulsions as a conservation strategy. One series of tests on the warm-air furnace was planned to show the effect of inadvertent use of w/o emulsions, such as might occur if water was accidentally or deliberately introduced to the fuel supply and the furnace was not adjusted to optimum performance. A second series of tests on both units was planned to show the deliberate water-in-oil use and therefore incorporated burner optimization.

Warm-Air Furnace

Three separate series of tests were conducted on the warm-air furnace and continuous measurements of nitric oxide, carbon monoxide and smoke number were obtained.

Fixed Combustion Air Setting. This series of tests was conducted to show the influence of the inadvertent introduction of water to a residential heating system. Initially, the cast-iron head burner with a 1.0 US gph firing rate was set up on No. 2 fuel oil according to the manufacturer's specifications and adjusted to steady operation at No. 1 Bacharach smoke number. Emulsions of varying water content (0 - 50% w/o) were then mixed in the small reservoir and supplied to the burner. No adjustment to the air control was made.

In each case the furnace was allowed to reach steady state. The efficiency decreased as the water content of the fuel was increased. Table

II shows an efficiency of 58.7% for an emulsion of 50% w/o, compared with 73.2% on No. 2 fuel oil. It was difficult to maintain ignition when water content was above 25%. Figure 1 shows that NO decreased and CO increased uniformly as the water content was increased. The smoke number, which initially had been set at No. 1, decreased to No. 0 at 4% w/o and remained at that level as the water content was increased further.

Constant Smoke Level Operation. For w/o ranging from 0.5% to as much as 60%, under conditions representing good operating practice (No. 1 Bacharach smoke number), four burner configurations were investigated — i.e., each burner head was operated at two nominal firing rates, 1.0 and 0.75 US gph.

Table II shows that the efficiency was about 73% for both nominal firing rates using the cast-iron head burner and a No. 2 fuel-oil supply. At the higher firing rate an initial efficiency increase to 75.2% was observed at 5% w/o with a subsequent continuous deterioration to 61.6% at 54.2% w/o. At the lower firing rate an initial efficiency increase to 74.4% at 0.5% w/o was observed with a subsequent continuous deterioration to 64% at 57% w/o. These differences between results at the two nominal firing rates can be attributed to changes in turbulence as the mass flowrate was varied.

In the case of the retention-head burner the efficiencies on No. 2 fuel oil were about 79% for both firing rates. Efficiency changed marginally, increasing only slightly between 2 - 15% w/o and thereafter decreasing continuously to about 76.7% at about 40% w/o for both firing rates. It appears that the retention-head burner, being more efficient, has less potential for improvement by using emulsions than does the cast-iron head, and is less sensitive to water content.

Figures 1, 2 and 3 show the variation of NO and CO with emulsion water content. For the cast-iron head a maximum (NO) or minimum (CO) is observed at about 5% for both firing rates.

NO levels with the retention-head are about double those of the cast-iron head when both are using No. 2 fuel oil. The retention-head burner operation shows no mazima or minima on NO and CO respectively, again indicating that this burner is not improved by emulsion firing. At high water contents with all burner configurations, CO increases and NO decreases, as expected.

Combustion and Emission Parameter Profiles. To compare combustion performance and emissions over a full range of operating conditions for the different burner configurations, each was operated on No. 2 fuel oil and 5% w/o emulsion over a full range of combustion air settings. These profiles are shown in Figure 4 and 5. In all cases it can be seen that the efficiency, smoke generation and flue gas temperature curves are only marginally changed by the addition of 5% water to the fuel.

Hot-Water Boiler

Steady running tests were conducted on the hot-water boiler at discrete w/o contents ranging from 0 to 20% by volume. Complete profiles of combustion efficiency, flue gas temperature and Bacharach smoke number were obtained over a full range of air supply from combustion air control fully closed to fully open. Figure 6 shows the profiles for both the cast-iron head and retention-head burner configurations when using No. 2 fuel oil and 5% w/o emulsion. From these data it was possible to establish the efficiency change as the water content was increased for a particular burner configuration. The efficiency improvement for both burner types is given in Table II and again it can be seen that the less efficient burner shows the greater potential for improvement.

In neither case is the efficiency change more than marginal, increasing from 85.2% with No. 2 fuel oil to 85.4% at between 1 to 5% w/o in the case of the retention head and from 78.2% with No. 2 fuel oil to 80.6% at between 1 to 5% w/o for the cast-iron head. Detailed measurements of emissions from this unit were not made but it can be seen from the smoke number profiles in Figure 6 that the emission of soot is unchanged by the addition of 5% water to the oil. This finding was fairly general over the full range of 0 - 20% investigated and for both burner configurations.

Operating Difficulties During the Test Program

The following problems, which might limit the potential of emulsions as residential fuels, were encountered during the test program:

1. Ignition difficulties and combustion instability when using emulsions above 25% w/o. This would influence such factors as cyclic operation and reliability for unattended use in residential heating applications.

2. Emulsion separation: usually after an overnight period the emulsion separated sufficiently to cause ignition and pumping difficulties even with low w/o content (<10% w/o). Usually the oil pump had to purged for 15 minutes with No. 2 fuel oil before constant pump pressure could be attained and the consequent ignition difficulties eliminated.
3. Pump failure: during the test program there were two oil pump failures which could be attributed to pumping emulsions over a 6-month period.
4. Furnace Deposits: analysis showed Fe present in deposits indicating corrosion products and causing concern over furnace life.

Conclusions

Studies on two residential heating systems have shown that water-in-oil emulsions do not present a viable energy, conservation strategy. Efficiency gains are at best marginal and do not outweigh increased operating difficulties associated with the use of emulsions, such as pump failures, furnace corrosion, ignition difficulties and combustion instablities due to emulsion separation. Far greater improvements in furnace efficiency and the corresponding energy savings can be better achieved using other documented conservation strategies.

Emissions of pollutants were influenced by increased water-in-oil content, but at practical levels of less than 10% water content changes were slight. Furnace efficiency deterioration and soot and CO emission increases at higher than 10% w/o make the choice of such emulsions for residential use impractical. In the laboratory the use of emulsified fuels gave rise to many operating problems; more can be expected in the field, particularly in the extreme Canadian winter.

Acknowledgements

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Table I. No. 2 fuel oil and emulsion flowrates* at selected w/o contents.

Nominal Water Content % by Volume	Firing Rate 1.0 US gph		Nominal Firing Rate 0.75 US gph	
	Emulsion flowrate US gph	No. 2 Oil consumption US gph	Emulsion flowrate US gph	No. 2 Oil consumption US gph
0 (No. 2 oil)	-	0.851	-	0.644
1.0	0.855	0.856	0.644	0.638
5.0	0.868	0.824	0.649	0.616
10.0	0.884	0.796	0.656	0.590
20.0	0.919	0.735	0.677	0.541
40.0	0.991	0.595	0.745	0.447
50.0	1.029	0.515	0.792	0.396

*Calculated from regression analysis of measured flowrate data.

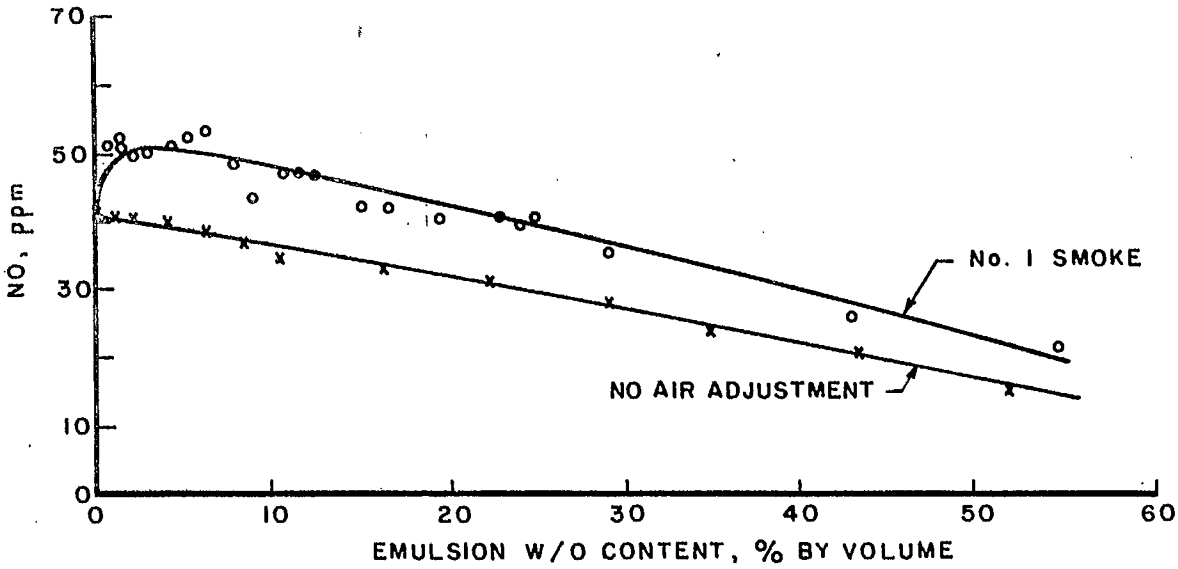
Table II. Efficiency changes in residential heating furnaces using w/o emulsions.

Furnace/Burner* Configuration	No. 2 Fuel Oil Efficiency %	Maximum Efficiency %	w/o %	Minimum Efficiency %	w/o %
WAF 1.0 CIH**	73.2	-	-	58.7	51.6
WAF 1.0 CIH	72.6	75.2	1.0 - 7.0	61.6	54.2
WAF 0.75 CIH	73.8	74.4	0.5	64.0	57.0
WAF 1.0 RH	79.4	79.7	4.1	76.9	34.7
WAF 0.75 RH	79.1	79.6	2.0	76.5	43.8
HWH 1.0 CIH	78.4	80.6	1.0	77.1	15.0
HWH 1.0 RH	85.2	85.4	1.0 - 5.0	84.4	20.0

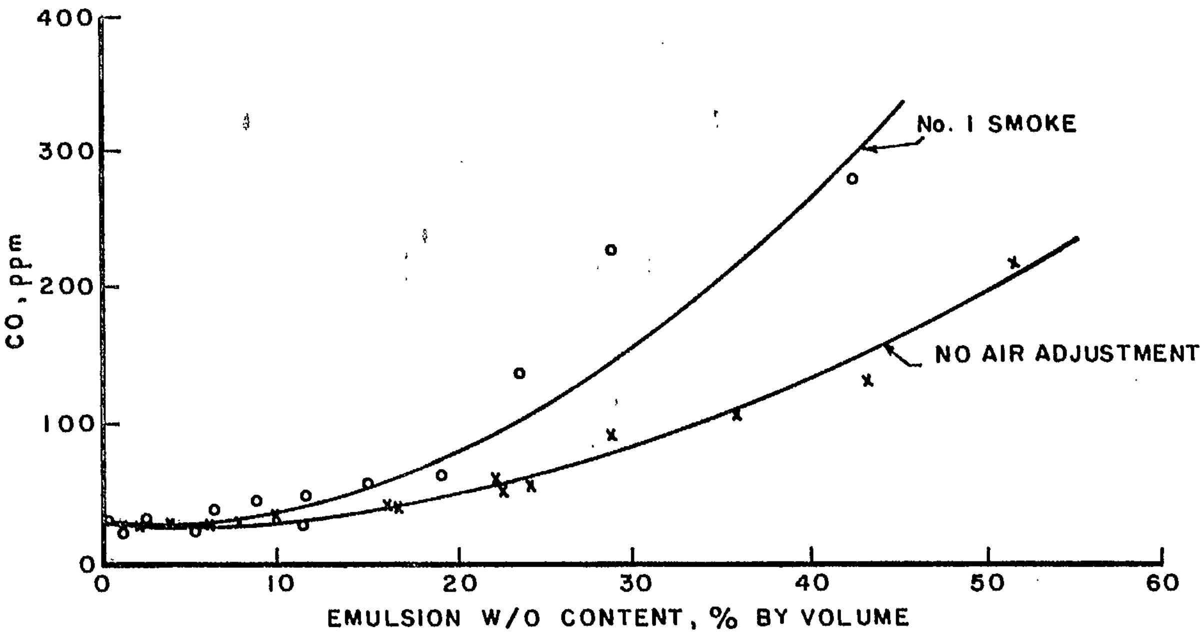
*HWH — hot-water heater
WAF — warm-air furnace
CIH — cast-iron head
RH — retention head
numbers represent nominal firing rates in US gph

** no combustion air adjustment

List of Figures

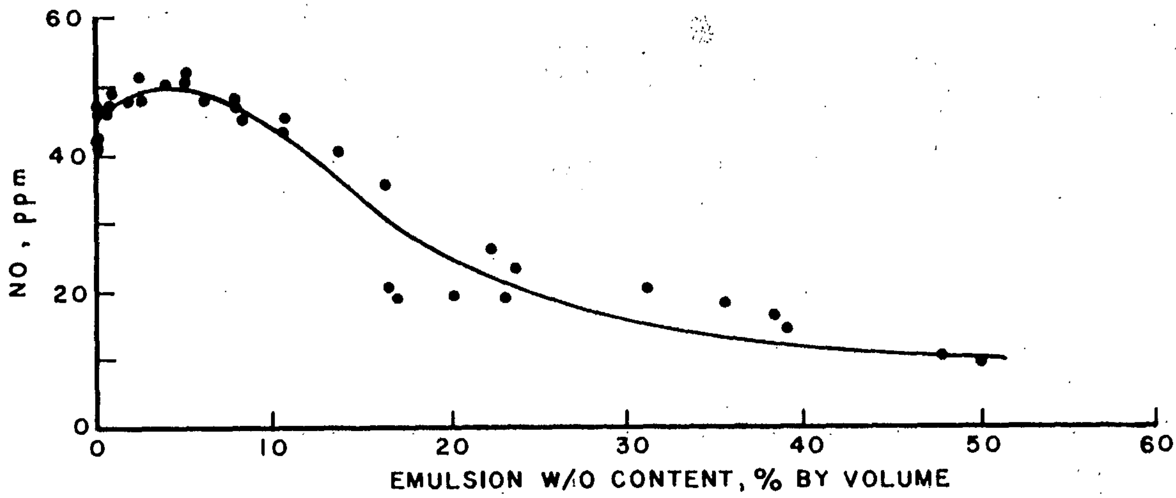


a) Nitric oxide formation.



b) Carbon monoxide formation.

Figure 1. Nitric oxide and carbon monoxide formation in the warm-air furnace: Cast-iron head burner with nominal firing rate 1.0 US gph.



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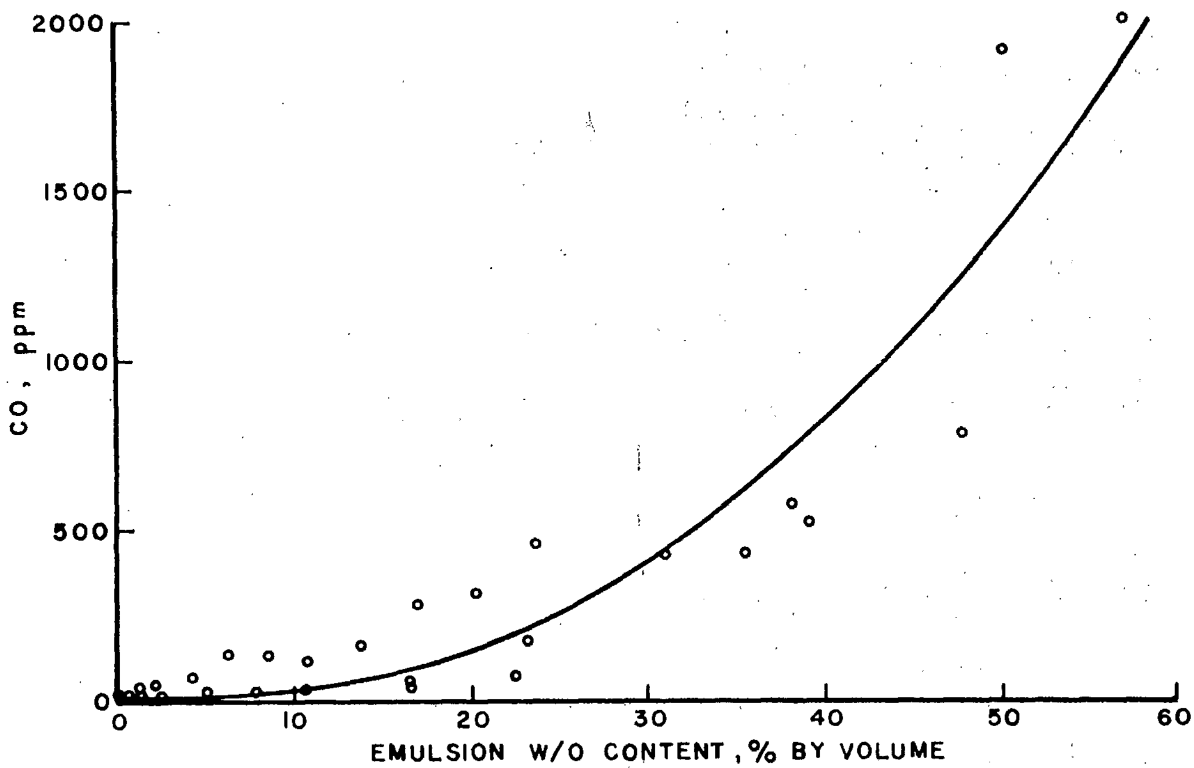
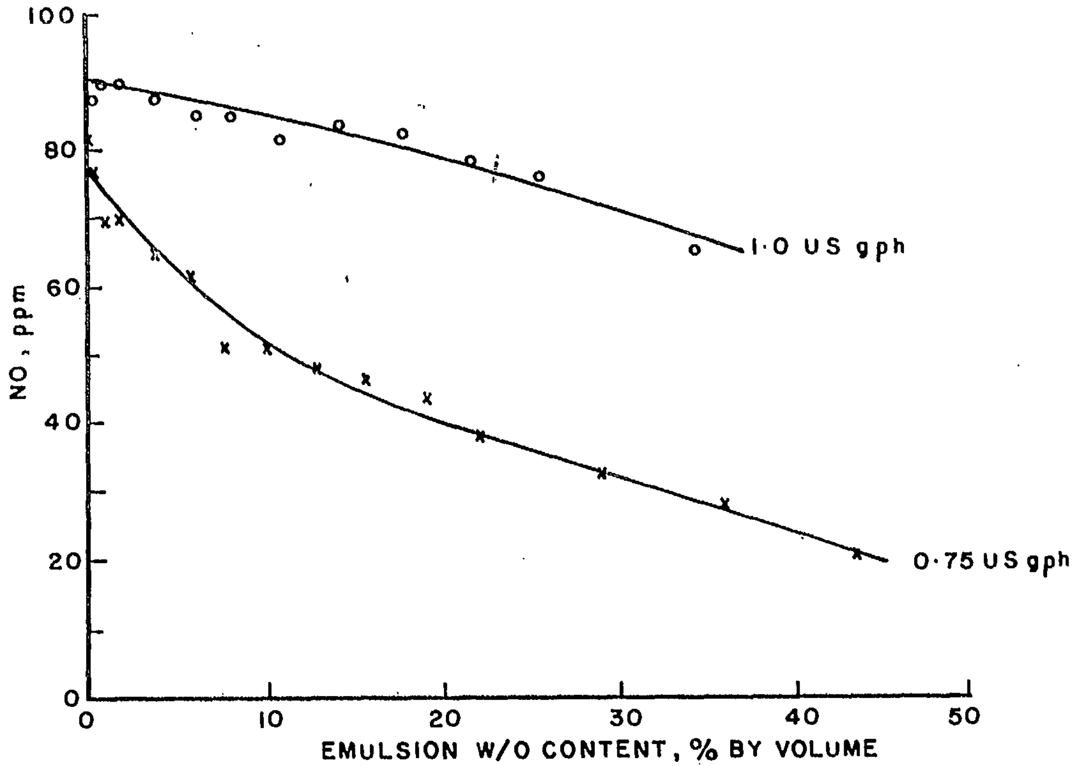
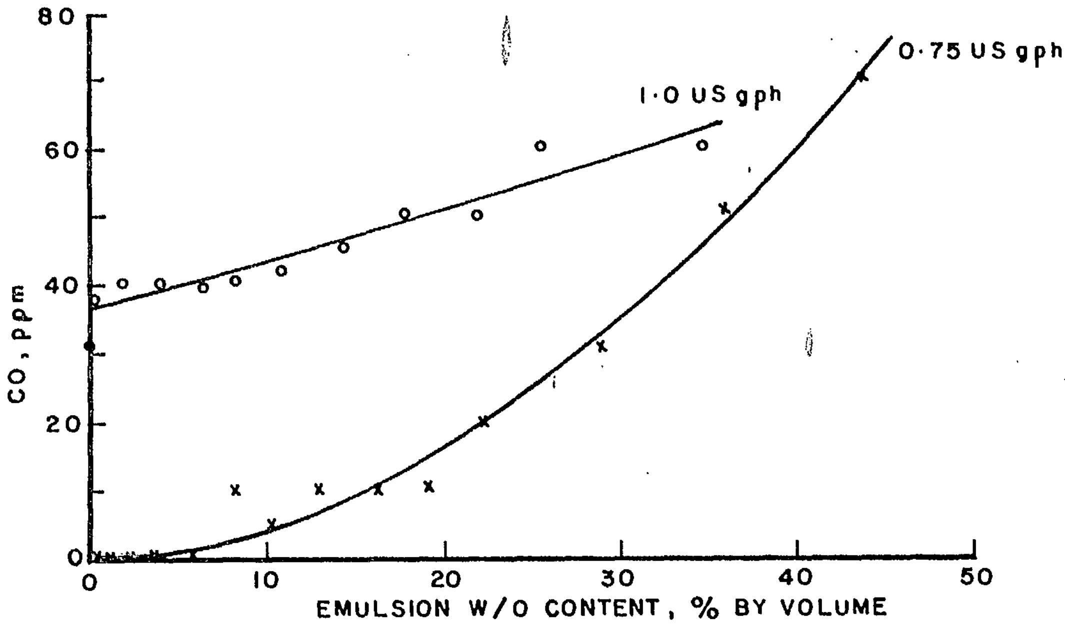


b) Carbon monoxide formation.

Figure 2. Nitric oxide and carbon monoxide formation in the warm-air furnace: Cast-iron head with nominal firing rate 0.75 US gph.

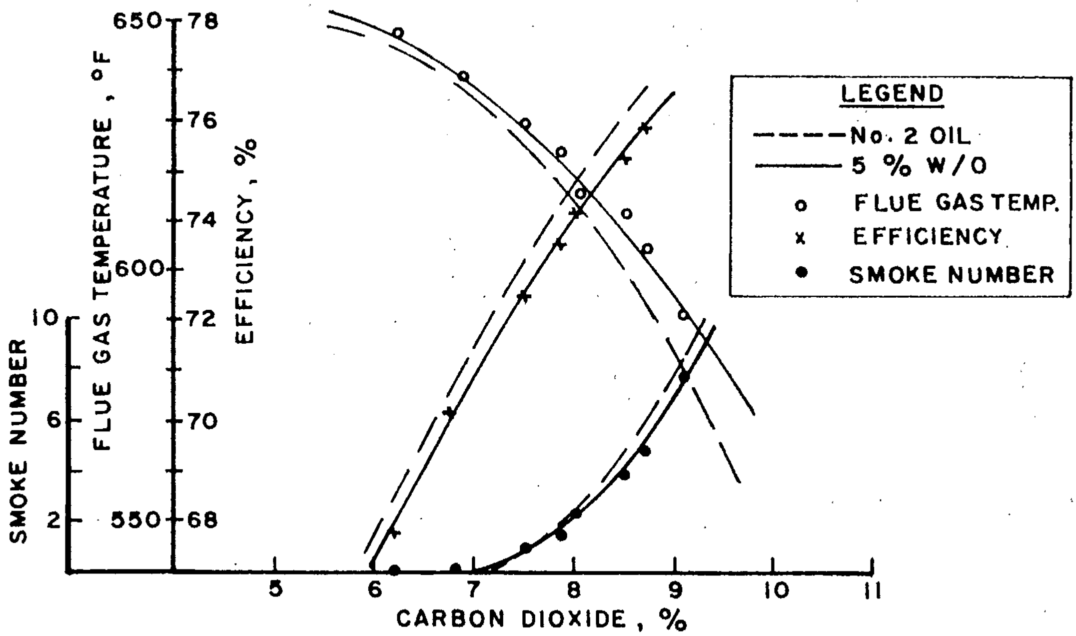


a) Nitric oxide formation.

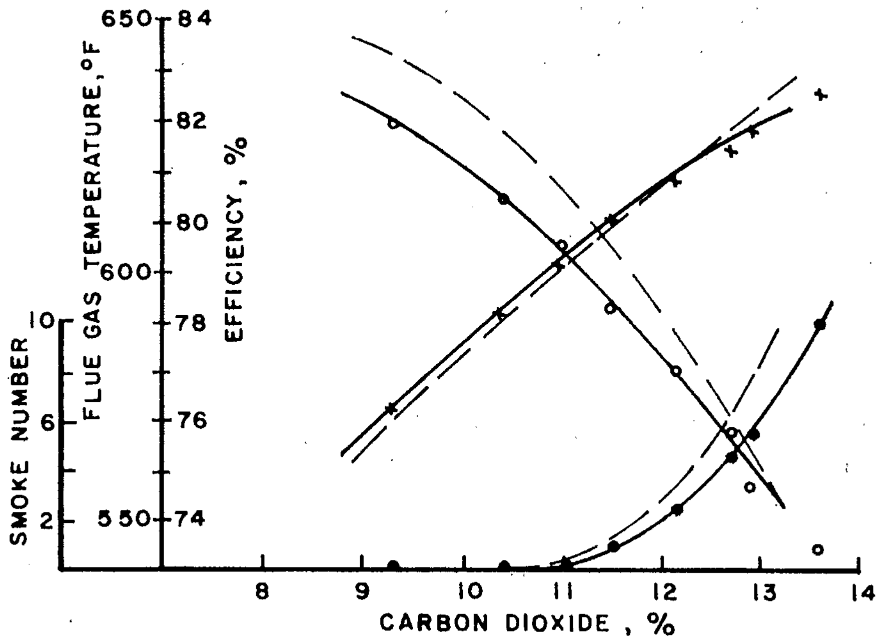


b) Carbon monoxide formation.

Figure 3. Nitric oxide and carbon monoxide formation in the warm-air furnace: Retention-head burner with nominal firing rates indicated.

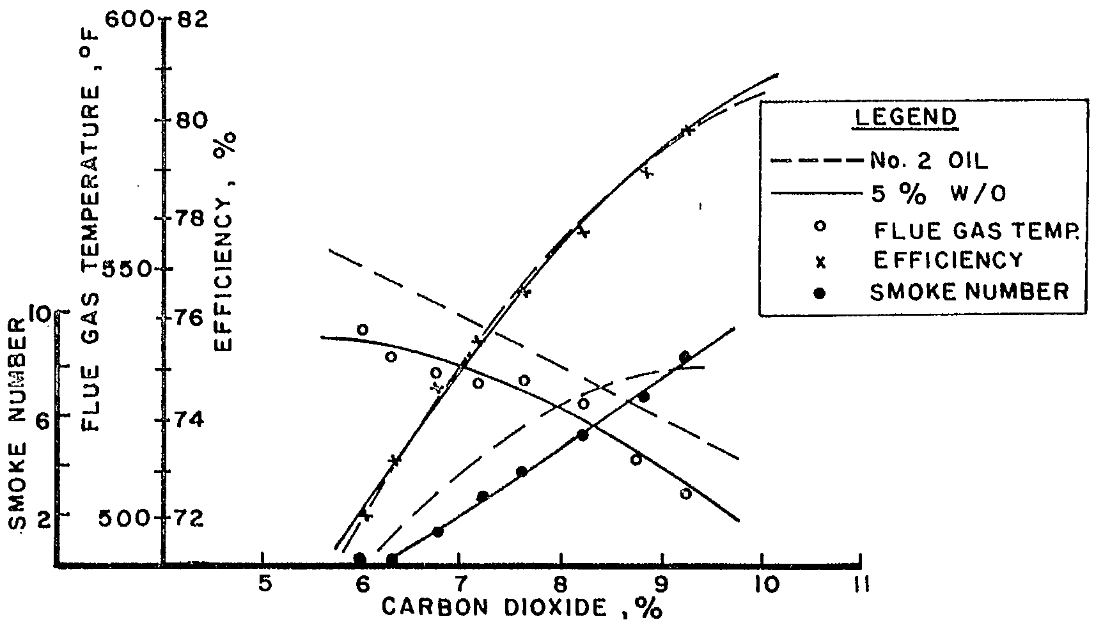


a) Cast-iron head.

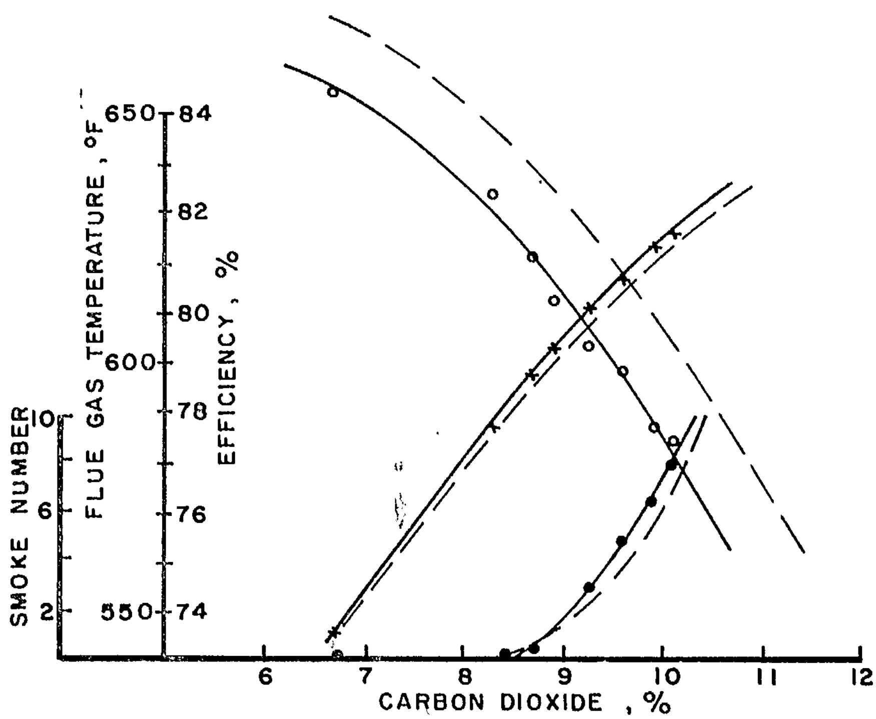


b) Retention head.

Figure 4. Combustion performance profiles for the warm-air furnace: Nominal firing rate 1.0 US gph, data points represent 5% w/o.

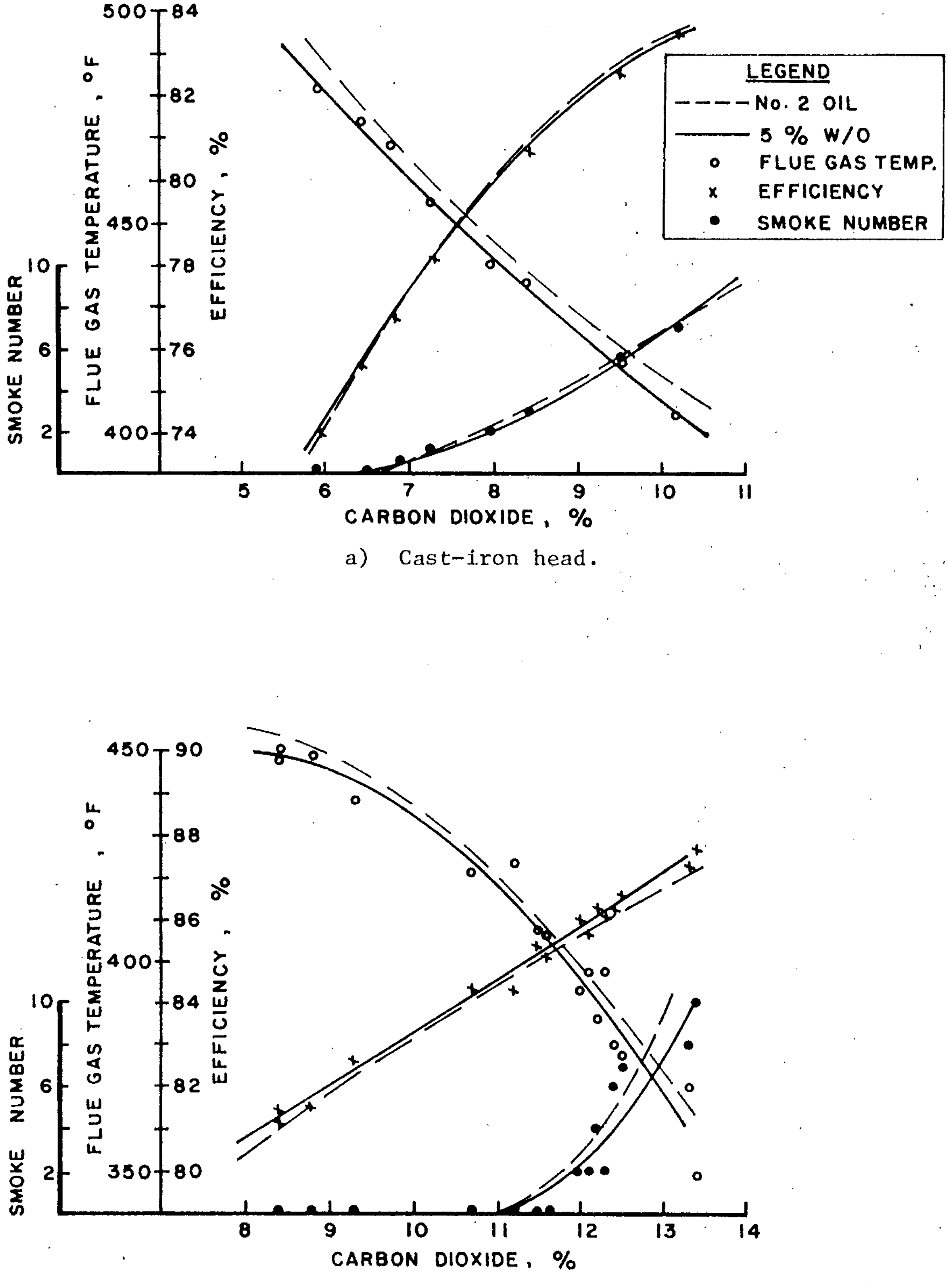


a) Cast-iron head.



b) Retention head.

Figure 5. Combustion performance profiles for the warm-air furnace: Nominal firing rate 0.75 US gph, data points represent 5% w/o.



a) Cast-iron head.

b) Retention head.

Figure 6. Combustion performance profiles for the hot-water heater: Nominal firing rate 1.0 US gph, data points represent 5% w/o.