Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

PERFORMANCE OF CONDENSING DOMESTIC GAS-FIRED HEATING EQUIPMENT

A.C.S.Hayden, C.E.Palmer and R.W.Braaten
Canadian Combustion Research Laboratory

February 1982

For presentation to the International Symposium on Pulsating Combustion and Condensing Heat Exchangers, Atlanta, Georgia, March 1982.

ENERGY RESEARCH PROGRAM
ENERGY RESEARCH LABORATORIES
DIVISIONAL REPORT ERP/ERL 82-23 (OP)

PERFORMANCE OF

CONDENSING DOMESTIC GAS-FIRED HEATING SYSTEMS

A.C.S.Hayden, C.E.Palmer & R.W.Braaten

Canadian Combustion Research Laboratory (CCRL)

SUMMARY

In Canada, conventional domestic gas-fired furnaces operate in the field at a low seasonal efficiency, in the range of 55-60%. The high hydrogen content of gas results in a large hydrogen loss; more efficient new technologies are attempting to condense the flue gases and recover some of the latent heat. This paper includes data from performance trials on a number of condensing gas-fired appliances. Units include a pulsating combustion boiler and a number of different warm air furnaces, fired with natural gas or propane. In the laboratory, steady state and cyclic tests have been run, with continuous measurements being taken on all components in the flue gas; the quantity and quality of the condensate generated is also determined. In the field, flip/flop trials are being conducted with a conventional gas or electric furnace as the baseline.

CCRL has commissioned the development of a stainless retrofit condensing flue system designed to be connected to an existing gas furnace or a converted oil furnace, to increase efficiency. Description of the design and laboratory performance of two prototype units are presented. A brief description of a promising new design of condensing furnace, using a plastic heat exchanger with recirculated flue gas to control temperatures, is also given.

INTRODUCTION

Conventional gas-fired heating systems operate at a low seasonal efficiency, between 55 and 60%, well below their steady state efficiency. Changes in technology could offer significant reductions in fuel consumption by improving combustion performance, reducing off-cycle losses, eliminating the need for downstream infiltration through the draft hood and increasing the steady state efficiency, to the point of condensing some of the water vapour present in the flue gas and regaining the latent heat.

In particular, because of its high hydrogen content, relative to No.2 oil, natural gas tends to suffer an efficiency penalty because of its high hydrogen loss, made up of the latent heat loss and the portion of the sensible heat carried by the water vapour. Having this high hydrogen content has also lead to the possibility of localized condensation at cold spots within the conventional heat exchanger, and the likelihood of corrosion therein.

With the gaseous fuels, natural gas and commercial propane having very low levels of sulphur along with high levels of moisture in their flue gases, it has become attractive to designers and manufacturers to overcome the limiting effects on efficiency with gas by making a determined effort to actually condense this vapour and regain much of the heat within a heat exchanger specifically designed for that purpose.

The Canadian Combustion Research Laboratory (CCRL), CANMET, Energy, Mines & Resources Canada, is conducting a research program in domestic gas-fired heating systems to help develop some of the most promising of the new technologies and to determine their performance, both in the laboratory under controlled conditions and in the field, under real-life conditions. Under this program the performance of a number of condensing furnaces, either in the prototype stage or actually on the market are being examined in detail, with the goals of improving the performance of the present units and making design modifications or developments for new units.

The results obtained to date, with a short description of some of the on-going developments are presented in the following paper.

HEAT LOSSES

There are two major heat losses up the flue of a residential furnace or boiler, the dry flue gas loss and the hydrogen loss.

The dry flue gas loss represents the sensible heat leaving the system up the stack, not considering the water vapour. It is dependent on the excess air and the difference in temperature between the flue gas and the combustion air. The lower the excess air or the lower the flue gas temperature, the lower the dry flue gas loss.

The hydrogen loss represents the energy associated with the water vapour present in the flue gas. It consists of the latent heat plus superheat, and is a function of the amount of water vapour remaining in the flue gas, the flue gas temperature and the combustion air temperature.

A more detailed description of these losses, and curves for their determination are presented in Reference 1.

An additional loss which can be significant is that due to the dilution air. This is heated house air which is entrained with the flue gas through the draft hood of a conventional gas furnace, downstream of the heat exchanger. For most installations, this air represents a major loss of warm air up the chimney while the furnace is operating. From Reference 2, the average dilution level is about 389%. This represents 5-7% in terms of heating load over a typical Ottawa heating season of 4763 Degree Days. It is the major air demand of the heating system, and can represent a supply problem in a tight house.

Another problem that the tight house creates is related to other air evacuating equipment, such as kitchen or bathroom fans, clothes dryers and "roaring" fireplaces. These can create prior demands on air related to most naturally aspirating gas-fired units. If the house is too tight, the easiest place for them to get air is down the chimney of the gas furnace. This disrupts combustion and can result in large amounts of carbon monoxide being released into the dwelling, with potentially catastophic results.

Another loss is due to the condensate and is merely the sensible energy in the condensate going down the drain; it is dependent on the amount of condensate and its temperature.

DESCRIPTION OF CONDENSING FURNACES/BOILERS

Four different types of condensing warm air furnaces and one type of condensing boiler were examined. The types of furnaces were as follows: condensing heat exchanger to concentric oil-type furnace, two types of finned tubed condensing heat exchangers to gas clamshell furnaces, and one stainless condensing clamshelll to a conventional clamshell, denoted by units B, C and F, respectively. The boiler, unit E, was the pulsating combustion type, similar in concept to one developed in Canada and tested by CCRL in 1965. Tests results for the original appliance are presented in Reference 3. A summmary of the characteristics of the different appliances is given in Table 1.

All of the warm air furnaces used an induced draft fan, downstream of the condensing heat exchanger, to evacuate the combustion products, which are then taken through a PVC pipe to the side wall of the house. Condensate is collected from the bottom of the stainless heat exchanger, as well as from a trap downstream of the fan and sent either directly to a drain or, if required by local regulations, neutralized in a holding tank with some basic solution before removal. This concept can effectively eliminate the potential for flow reversal under poor draft, such as was described in the previous section.

Retrofit Condensing Furnace

Recognizing that most of the existing gas-fired furnaces in Canada operate at a relatively low efficiency over the heating season, on the order of 55% to 60%, CCRL is carrying out a major program to develop equipment which could be used to upgrade these existing furnaces to the very high levels potentially available with the new advanced performance equipment now entering or about to enter the marketplace. The implementation procedure wil be similar to a prior program on oil-fired equipment, as detailed in Reference 4. The general configuration of the condensing furnaces is shown in Figure 1.

In particular, one of the retrofit packages, which has been produced under contract to CCRL by a major furnace manufacturer, as detailed in Reference 5, is designed to convert a conventional gas furnace into a condensing unit. The technique is similar to the condensing furnaces previously described, whereby there is a conventional front end furnace, to date fired only with naturally aspirating burners, and a second add-on portion with a stainless steel heat exchanger and induced draft fan, as shown in Figure 1. The draft hood can either remain or, preferably, can be sealed up. Units A and D are prototype retrofit systems when connected to conventional gas furnaces G and H and fired with propane and natural gas, respectively.

EXPERIMENTAL PROCEDURE

Laboratory

Detailed tests are performed on each furnace, at three conditions, to measure its performance. Each unit is run for a continuous 3 hour run to obtain accurate steady state information. Then the cycling test as prescribed by the U.S. Department of Energy to measure a cycling (seasonal) efficiency, consisting of a long on-cycle to steady state, off for 20 minutes, on for 30 minutes, off for 40 minutes and on for 30 minutes. Finally, a series of 10 minute on 30 minute off cycles are run.

Flue gas components are measured with continuous analyzers, as follows: carbon dioxide and carbon monoxide with infrared; oxygen with paramagnetic; and nitrogen oxides with chemiluminescence. All relevent temperatures are measured with thermocouples. The data are collected by a data logging system and stored on magnetic tape for subsequent computer reduction. Condensate collected from within the furnace proper was separately collected weighed and analyzed for acidic components. Downstream condensate was also examined.

In addition to tests corresponding to design conditions, additional parametric runs were carried out on the pulsating combustion boiler. It was run at a series of inlet (return) water temperatures, with the exit temperature held constant at 65°C, except for the last set, where the outlet temperature was allowed to rise to 80°C.

Field Measurements

In the field, flip-flop trials are being conducted over the heating season, with a conventional gas or electric furnace as the baseline. Depending on the character of the heating period, each furnace runs for one or two weeks at a time, then the other unit is operating, and so on so that a good distribution of performance data is obtained over the whole range of the heating season. The furnaces are instrumented to provide specific gas or electricity consumption, time of operation and number of cycles, along with at least hourly measurements of ambient conditions. Data is placed on magnetic discs for subsequent reduction in a procedure used in Reference 6.

A pulsating combustion boiler and a condensing furnace are being tested in occupied homes of conventional construction, as part of a contract to determine the performance of a number of advanced technology gas-fired appliances, to Consumers' Gas by CCRL, as outlined in Reference 7. A different condensing furnace is installed in an unoccupied, fully instrumented, high efficiency house, built for detailed energy analysis in companion with three other similar units. This second trial is being carried out in cooperation with HUDAC, Consumers' Gas and the National Research Council of Canada.

FUELS AND THEIR CHARACTERISTICS

Fuel Composition

Either natural gas or propane was used in the appliances. Analyses of these fuels are presented in Table 2, both in terms of the molar distribution of the various hydrocarbons, and in terms of their ultimate analyses. The amount of carbon in natural gas is considerably lower than that for propane, 71.6% as to 81.7%, with a commensurate difference in heating value.

Water Dewpoint

The water dewpoint is the temperature at which the liquid and vapour phase exist simultaneously in equilibrium. If the temperature is lowered below the dewpoint, water will begin to condense. For any particular fuel, the water dewpoint of the flue gas at stoichiometry is a function only of the hydrogen/carbon ratio in the fuel. The H/C ratio ranges from natural gas at 0.32, to propane at 0.22, to No.2 oil at 0.15.

Combustion systems do not operated at stoichiometry, but rather at some higher level of excess air. This dilution effectively lowers the concentration of water vapour in the flue gas per unit volume. The greater the excess air, the lower the dewpoint. Figure 2 shows the variation in dewpoint with excess air for the two fuels mentioned, as well as for No.2 oil and methanol.

It should be noted that at any particular excess air level, the dewpoint for propane is about 5°C lower than for natural gas; thus, any unit firing propane will likely have to "work harder" to achieve the same level of efficiency (or at least, condensate) than one firing natural gas.

EXPERIMENTAL RESULTS

Tables 3a and 3b present a summary of the results obtained from steady state experiments on the various furnaces, firing propane and natural gas, respectively. For comparative purposes, data for two conventional furnaces, fired with the same fuels, are also given.

From Table 3a, the two propane furnaces behaved similarly. While operating at a slightly higher excess air level, the retrofitted furnace, unit A, was able to achieve 1% better efficiency, probably because of slightly better heat transfer. The amount of condensate generated was up. However, both units actually produced very little condensate, 18% and 13% of that possible. Ph levels of the condensate were similar, about 3. Flue gas temperatures were 9°C and 18°C above the dewpoint. It is anticipated that better performance would be obtained when firing natural gas, where the dewpoint would be some 5°C higher.

Because of the low exit temperatures, very little sensible heat remains in the flue gas; the dry flue gas loss is low, less than 20% that of the standard furnace. Thus even though little condensation is achieved, efficiencies are still high, over 90% in both cases.

From Table 3b, the furnace exit temperature of unit C is quite high. Even so, it does achieve 24% condensation, the largest amount among the warm air furnaces. It is the temperature at the surface of of the metal and the surface film which actually governs the amount of condensate. Also, if a bank of tubes are used as the condensing heat exchanger, feeding a single manifold, as in Figure 2, it is possible to have individual tubes which are quite cold and condense much of the vapour that passes through them, while other tubes are quite hot, and achieve only marginal condensation. This is what happens with furnace C. Gases in the outer tubes were very cold, while the inner tubes remained very hot. The blended final temperature was 78°C; this is 21°C above the dewpoint. Based solely on the exit temperature, little or no condensation should have occured.

Comparing furnace C and boiler E, both units are operating at very low excess air levels. The boiler has the highest efficiency, primarily because of a low flue gas temperature. The dry flue gas loss for this unit is less than 1%. Furnace C has an exit temperature 26°C higher, so that its dry flue gas loss is doubled, although still low at 1.9%. Condensate levels are similar, with the boiler 6 percentage points higher.

Furnace D, the other retrofit unit, also has an exit temperature similarly above the dewpoint, even though the actual temperatures were lower due to the higher excess air levels. However, there was very little stratification in the tubes, so that there was not the localized condensation that occured in unit C. Efficiency was slightly lower at 88.2%, and only 16% of the water was condensed.

Furnace F has the lowest efficiency, with effectively no condensation, even though it was the only warm air furnace with a flue gas temperature actually below the dew point. This unit has a single stainless clamshell as the condensing heat exchanger, so that there is no localized cooling. Its high excess air yields an efficiency of just below 85%.

Effect of Cycling Time on Condensate and Efficiency

Recognizing that a furnace does not run for the same length of time over the whole heating season, it was desired to determine what effect cycling time would have on condensing furnace performance. From Reference 6, an average cycle length in Ottawa is between 10 and 16 minutes for a warm air furnace, with only half that for boilers. Shorter cycles occur in the milder portions of the heating season, and longer ones in the coldest portion. Since the driving force for condensation is metal surface temperature, it appeared likely that shorter on cycles would produce more condensate per unit of fuel fired.

Table 4 presents the mean results for the four different firing conditions of unit A. In changing from the long steady state run of 3 hours to the DOE cycling run, there was very little difference. This was borne out by similar tests on unit C. However, when the on-time was reduced to 10 minutes, nearly twice as much condensate was produced; the hydrogen loss was reduced and the efficiency was increased by 0.8%. Reducing the cycling time still further, to 5 minutes on, shows a further increase in condensate production of 62%, with another efficiency gain of 1%. In this case, the excess air was increased to somewhat offset the gain due to condensate.

Performance of Condensing Boiler

Table 5 gives the experimental results for the condensing boiler at a series of inlet water temperatures from 25°C to 60°C, with the outlet temperature held constant at 65°C. The final run set the inlet water to 65°C and let the outlet temperature rise to 80°C.

As expected, the results show the performance strongly sensitive to inlet water temperature, especially at the lower levels. At 25°C, more than 50% of the water vapour was condensed, and the highest efficiency, 94.5%, was achieved. Increasing the water temperature from 25°C to 40°C decreased the condensate flow by 40% with a similar increase in the hydrogen loss. The efficiency fell 2.8% to 91.9%.

The other interesting observation is that the efficiency for this unit was as least as high as for any of the condensing furnaces, even though they were operating with much more suitable return temperaturs for condensation.

Field Trials

Due to problems with delivery of equipment, data is only available for the trial comparing the condensing boiler with a conventional unit. From Reference 7, the steady state efficiencies were 88.9% and 77.0%. Average consumptions per degree day were 18.5 kBtu and 27.8 kBtu, respectively. On this basis, the condensing boiler showed a 33% fuel saving over the heating season.

More detailed results on this installation, along with the other two described, will be available at the end of the present heating season.

NEW DEVELOPMENTS

One promising new development which has been produced under contract to CCRL is a condensing furnace which operates in a similar manner to the other Canadian furnaces previously described in that it is effectively an add-on to a conventional gas furnace. However, this unit is quite distinct in that it is using a plastic for the condensing heat exchanger, rather than the stainless steel that the other units utilize. The plastic is arranged in layers ressembling torsion boxes to build up a cross-flow heat exchanger. The other unique feature is a recirculation mechanism bringing a large portion of the flue gases back to the front of the condensing heat exchanger to control the inlet temperature to acceptable levels for the plastic. A schematic of the unit is shown in Figure 3. If the life of the plastic is satisfactory, this will be a major way that the cost of the condensing furnaces may be kept to reasonable levels. A further contract will be let this year to optimize the system design and components, as well as to ensure compatibility of the materials to the potentially corrosive condensate, as well as to produce three working prototypes will be produced for field evaluation over the next heating season. A more detailed description of this unit appears in Reference 8.

CONCLUSIONS

1. Efficiencies are in the order of 90% for all the units that achieve condensation.

2. None of the units examined condense the majority of the water vapour present in the flue gas, under normal operation.

3. The major efficiency gain comes from reducing the dry flue gas loss (sensible heat), not the hydrogen loss (latent heat).

4. Cycle length is an important criterion for any experimental test to estimate seasonal performance; the shorter the cycle, the greater the amount of condensate generated per unit of fuel burned.

5. Retrofit condensing flue systems are practical, and offer the same level of performance as new condensing furnaces.

7. A new plastic cross-flow condensing heat exchanger with recirculation offers potential for increasing efficiency while reducing equipment costs.

REFERENCES CITED

1. Friedrich, F.D. & Hayden, A.C.S., Combustion Handbook for Canadian Fuels, Volume II/ Gaseous Fuels, M.B. Mono 879, 1973.

2. Hayden, "Efficient Gas-Fired Heating Systems", Proceedings, Annual Meeting of Combustion Institute, Cdn Section, May 1981.

3. Alebon, J., Lee, G.K. and Geller, L.B., "A Pulsating Combustion System for Space Heating, FMP 63/47-MECH, Ottawa, 1963.

4. Hayden & Braaten, "Efficient Residential Oil Heating Systems", A manual for servicemen, designers and builders, El 79-8, EMR.

5. Clare, E.C., "A Retrofit Package for Gas-Fired Furnaces", Statement of Work for Contract 23440-9-9003, from Energy, Mines & Resources Canada to Clare Bros. Ltd., ACS Hayden - SA, Dec. 1979.

6. Hayden, Braaten & Brown , "Oil Conservation in Home Heating", ASME Jnl of Engineering for Power, January 1977.

7. Shearer, D.R., "Field Evaluation of Improved Domestic Gas Furnaces Initial Test Data Report", Contract 23440-0-9142 with Consumers' Gas, ACS Hayden - Scientific Authority, June 1981.

8. Wright, J.L. & Sullivan H.F., "Conceptual Designs of High Efficiency Residential Gas Furnaces", Report on Phase I of Contract 23440-0-9148 with Consumers' Gas & Spyder Engineering, ACS Hayden - Scientific Authority, November 1981.

Table 1. Furnace and Boiler Characteristics.

Furnace Boiler	Burner	Firing Rate kB/hr	Condensing Heat Exchanger	New or Retro	Fuel
Furn A	N.A.	88.4	Finned tube stainless	retro	propane
Furn B	"	89	"	new	"
Furn C	"	95	"	"	nat gas
Furn D	"	111	"	"	"
Blr E	pulse	97		"	"
Furn F	N.A.	85	Clamshell stainless	"	"
Furn G	N.A.	90	none	"	propane
Furn H	"	110	none	"	nat gas

Table 2. Fuel Analyses.

	Mole %	
	Propane	Natural Gas
Methane		91.57
Ethane	3.40	5.01
Propane	95.10	0.25
Butane	1.50	0.01
Pentane	-	trace
Nitrogen		2.65
Carbon Dioxide		0.49
Higher Heating Value, Btu/Scf	2544	1007
	Ultimate Analysis, % by weight	
Carbon	81.7	71.6
Hydrogen	18.3	23.2
Nitrogen		4.3
Oxygen		0.9

Table 3a. Furnace performance at steady state, propane-fired.

Furnace	Excess Air, %	Flue Gas Temp, °C	Dry Flue Gas Loss, %	Hydrogen Loss, %	Dewpoint °C	Efficiency %	% Condensed	pH
A	104	50.5	2.0	6.8	41	91.2	18	3.0
B	98	58.9	2.3	7.4	40	90.4	13	3.2
G	69	269	12.6	9.4	47	78.0		

Table 3b. Furnace performance at steady state - natural gas.

Furnace	Excess Air, %	Flue Gas Temp, °C	Dry Flue Gas Loss, %	Hydrogen Loss, %	Dewpoint °C	Efficiency %	% Condensed	pH
C	13	78	1.9	7.6	57	89.5	24	3.8
D	163	62	3.1	8.6	40	88.2	16	2.9
E	21	52	0.9	7.0	55	91.9	30	5.7
F	111	49	3.8	10.3	50	85.9	3	4.0
H	52	191	7.8	11.2	53	81.0	-	-

Table 4. Effect of cycling time on efficiency and amount of condensate.

Test condition	Hydrogen Loss %	% H_2O Condensed	Efficiency %
A - 3 hour	6.8	18	91.2
B - 3 hour	7.3	13	90.4
A - DOE cycling	6.9	17	91.2
B - DOE cycling	7.0	16	90.8
A - 10 min cycling	6.2	25	91.8
B - 10 min cycling	6.3	25	91.7
A - 5 min cycling	4.9	42	93.0
B - 5 min cycling	5.1	39	92.8

Table 5. Effect of inlet water temperature on the performance of condensing boiler.

T_{in} °C	dT °C	Excess Air,%	Flue Gas Temp.,°C	% H_2O Cond.	DFG Loss,%	Hydrogen Loss, %	S.S. Eff. %
25	40	20	38	51	.48	4.93	94.5
40	25	21	52	30	.93	7.03	91.9
55	10	13	58	21	1.04	7.57	90.9
60	5	13	60	14	1.14	8.73	90.0
65	15	13	58	4	1.10	9.72	89.2

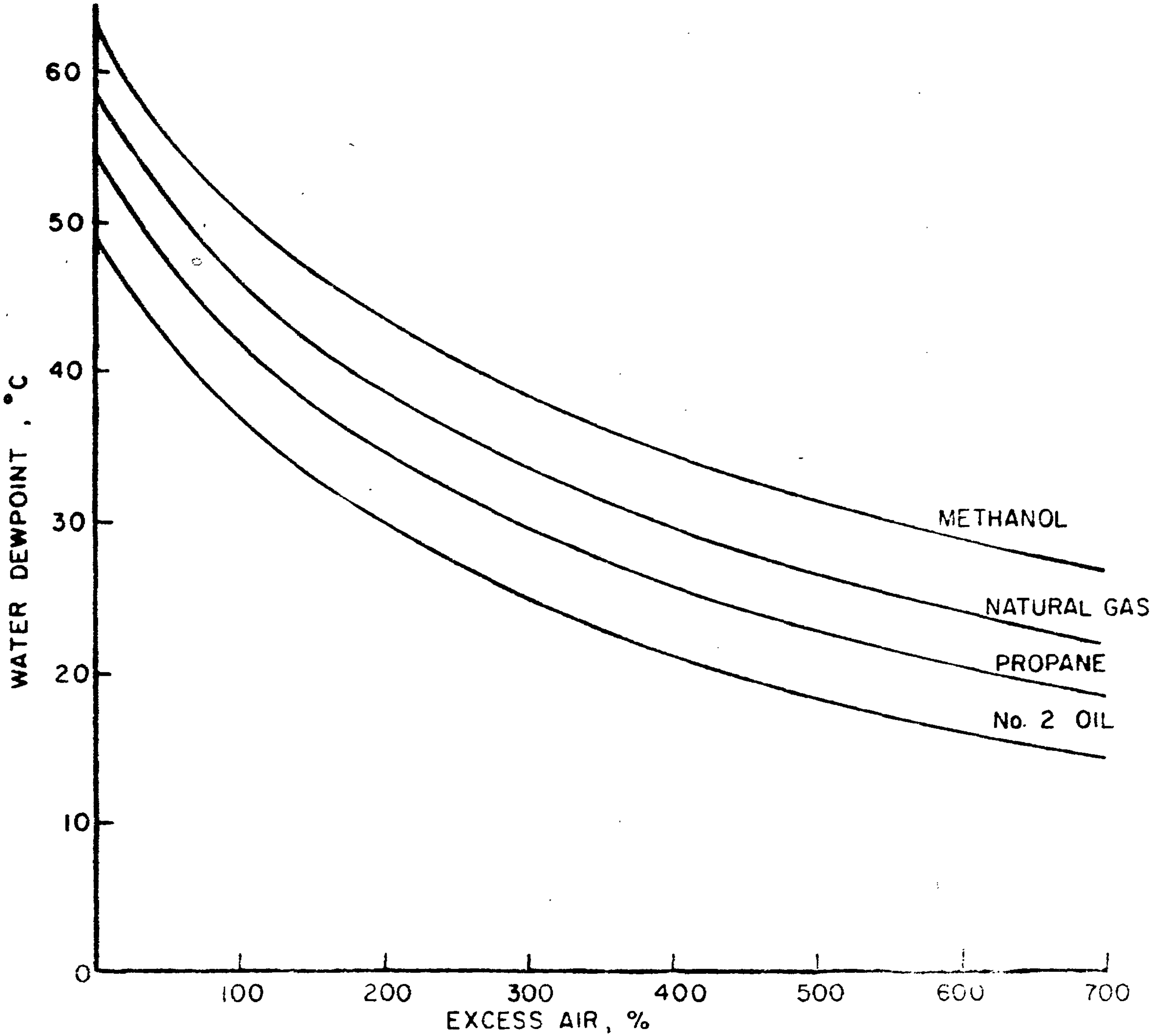
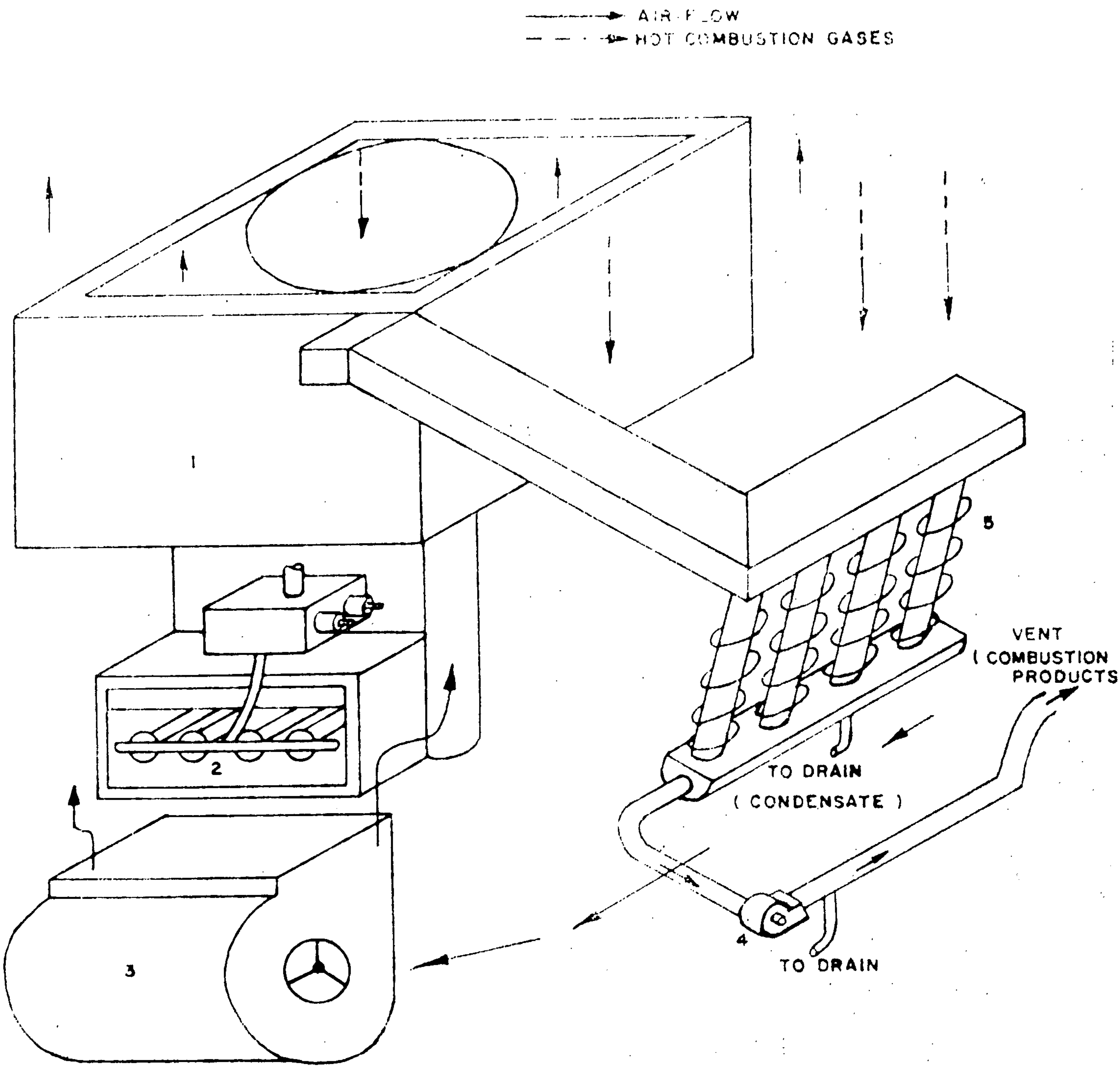


Figure 1. Variation in water dewpoint with excess air for different fuels.



1 MAIN HEAT EXCHANGER
2 ASPIRATING GAS BURNER
3 CIRCULATING FAN
4 INDUCED DRAFT FAN
5 CONDENSING HEAT EXCHANGER

Figure 2. Condensing furnace with stainless finned tube heat exchanger.

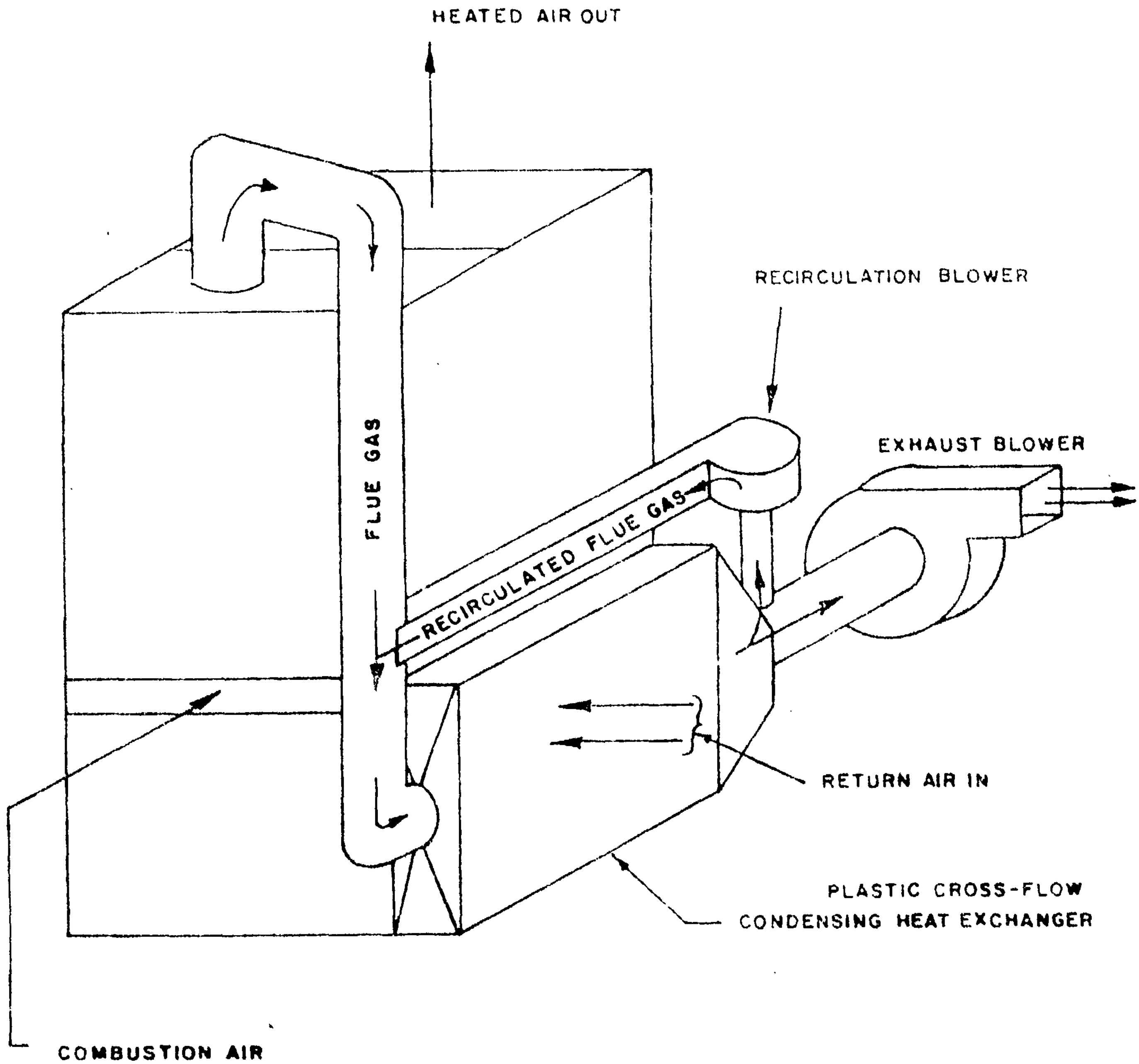


Figure 3. Prototype condensing furnace with plastic heat exchanger and recirculated flue gas.