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LIQUID AND COLLOIDAL ALTERNATIVES TO CONVENTIONAL LIQUID FUELS

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by

T. D. Brown* and G. K. Lee*

ABSTRACT

Limited availability of conventional No. 2 fuel oils led to a combustion investigation of two refinery residues and two coal-in-oil slurries as potential substitutes. The investigation was carried out in a calorimetric tunnel furnace using a mechanical-atomizing burner for the refinery residues and a low pressure air atomizing burner for the coal-in-oil slurries.

At two swirl levels (S = 0.26 and 0.51) and three excess-air levels both of the refinery residues showed combustion efficiency, heat transfer and pollutant emission characteristics similar to those of No. 2 oil. No. 6 oil was comparable to the three high quality fuels at all but the low swirl condition when heat transfer rates and pollutant emissions were relatively high.

The coal-in-oil slurries (33% coal in No. 2 oil) were successfully prepared and burnt using commercially available hardware. With lignite, combustion was essentially complete at both 25% and 7.5% excess-air; however, with a bituminous-coal washery-reject the fly ash contained about 45% combustible matter at 25% excess-air. Petrographic examination of the two coals revealed that the bituminous coal reject contained over 60% fusinite and semi-fusinite. These two macerals burn slowly and were considered to be responsible for the poor burn-out of the bituminous coal reject.

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CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Page

INTRODUCTION

In Canada, the Department of Energy, Mines and Resources is the principal federal agency responsible for the development, utilization and conservation of the country's mineral and energy resources. Within this department are a number of groups engaged in a co-ordinated research program which is directed toward the development of specific energy technologies for national use. The Canadian Combustion Research Laboratory (CCRL) is one of these groups and provides a focal point for applied combustion research in Canada.

The current research program at CCRL falls into two general categories. The first is the "in-house" program of research into combustion and combustion-related processes; this includes activities such as the combustion characteristics of low-quality fuels, combustion aerodynamics, burner development, detrimental effects of fuel residues and fluid-bed combustion. The second involves collaborative research programs with Canadian industry on problems such as performance evaluations of existing equipment, the enhancement of electrostatic precipitator performance for low sulphur coals and chimney plume dispersion studies, to name a few.

This paper is concerned with two complimentary studies, one taken from each of the two research categories explained above.

Investigation of the liquid fuel alternatives to conventional fuel oils was undertaken in collaboration with a Canadian steel company to assess the feasibility of substituting two liquid refinery residues for distillate and residual fuel oil in industrial heat processes. Both alternative fuels offered price and availability advantages to the consumer.

The investigation of the colloidal fuel as an alternative to conventional liquid fuels was undertaken as part of the "in-house" research program at CCRL to establish design parameters for burning a colloidal coal-in-oil fuel in commercially available combustion equipment.

THE EXPERIMENTAL FURNACE

The CCRL tunnel furnace used in both series of experiments described in this paper has been reported in detail elsewhere[1]. It is a horizontal cylindrical furnace consisting of 28 individual calorimetric sections with a total length of 4.25 m and a diameter of 1 m. The maximum thermal input is 2000 MJ/hr (0.56 MW). Figure 1 is a side view of the furnace showing the mechanism for handling flame probes.

The furnace coolant (Therminol FR 1) is a fire-resistant chlorinated biphenyl which remains stable at atmospheric pressure over a temperature range from 0 to 315°C.

LIQUID ALTERNATIVES TO CONVENTIONAL FUEL OILS

The objectives of this study were to determine the suitability of two liquid refinery residues as substitutes for conventional No. 2 distillate fuel oil and No. 6 residual fuel oil by characterizing the following:

1) The physical and chemical properties of each fuel with particular attention being paid to pumpability and flash point.

2) The effects of low- and high-swirl numbers in conjunction with three excess combustion-air levels on flame characteristics, heat flux distribution, particulate emissions and gaseous pollutants.

Fuel Properties

The two substitute liquid refinery residues were derivatives from a synthetic (tar sand) crude oil and a natural crude oil. Each sample, comprising 7 barrels, was uniformly blended in a 500-gal mixing tank at CCRL before being analyzed and burned. These refinery residues are identified here as synthetic derivative (SD) oil and natural derivative (ND) oil. Both the No 2 and No. 6 reference fuel oils used in this project met ASTM Specification D396-69 for commercial fuel oils.

The analyses of all four fuels are given in Table 1. From this table it can be seen that the most dramatic differences in fuel properties were in kinematic viscosity and pour point, which significantly influence fuel atomization and air-fuel mixing patterns. These two properties, together with flash point, are normal accepted indicators that the No. 2 oil and the SD oil should burn efficiently without preheat whereas the ND oil should be preheated to about 38°C for good combustion and easy pumpability.

The Experimental Burner

The furnace was fired with a specially-designed, mechanical-atomizing burner which incorporated infinite control of the secondary-air swirl; the primary air was given a constant low-swirl component sufficient to stabilize the flame. The burner, shown in Figure 2, was fired at about 12.5 US gph or 90% of full-load rating of the tunnel furnace. Specified control parameters for each of the four fuels were as follows:

1. Excess combustion air corresponding to 1%, 3% and 5% O_2 in flue gas.
2. Swirl numbers (isothermal at 21°C): 0.3 and 0.5.
3. CO in flue gas: 0.1 or less.
4. Smoke opacity: Number 1 Ringleman or less

TABLE 1

Analyses of the Four Fuel Oils

	No. 2 Oil	SD Oil	ND Oil	No. 6 Oil
Specific Gravity, 15.6/15.6°C	0.888	0.880	0.908	0.980
A.P.I. Gravity at 15.6°C	27.9	29.3	24.3	12.9
Flash Point, °C	60	0	130	77
Pour Point, °C	-34	-23	27	-
Kinematic Viscosity, cSt				
at 25°C				578
at 50°C	2.00	3.87	16.96	
Ultimate Analyses				
Carbon, % wt	85.25	86.47	86.33	86.48
Hydrogen, % wt	12.26	12.55	12.57	11.02
Nitrogen, % wt	0.01	0.06	0.06	0.10
Sulphur, % wt	0.26	0.32	1.46	2.40
Gross Heat of Combustion Kcal/Kg	10,900	11,393	11,300	10,184

Performance Parameters

The sampling locations used for measurement of the principal parameters listed below are shown in Figure 3.

1. CO_2 and CO continuously by infra-red analyzer at Stations 1, 2 and 3.
2. O_2 continuously by paramagnetic analyzer at Stations 1, 2 and 3.
3. NO continuously by chemiluminescent analyzer at Station 3.
4. Gaseous hydrocarbons continuously by infra-red analyzer at Station 3.
5. Axial velocity intermittently by hammerhead-pitot tube at Stations 1 and 2.
6. Temperature by high-velocity thermocouple at Stations 1 and 2 and by stagnation thermocouple at Station 3.
7. Heat flux intermittently by IFRF probe at Stations 1 and 2.
8. Smoke opacity intermittently by Van Braun recorder at Station 3.

With the exception of heat flux, which was taken flush with the furnace wall, all measurements at Stations 1 and 2 involved probing across the flame diameter using the traversing mechanism shown in Figure 1. At Station 3 all measurements were taken at the centre of the flue gas duct under essentially plug-flow conditions.

The two flames selected for examination were defined aerodynamically by the following rotational flow characteristics:

(a) Low-Swirl Flame: This is a flame in which the secondary combustion air is introduced without any significant rotational component of velocity.

(b) High-Swirl Flame: This is a flame in which the secondary air is introduced with a significant rotational component of velocity to produce a recirculation core downstream of the burner quarl.

The secondary air vane settings for the desired low- and high-swirl numbers were predetermined by cold isothermal probing with a 5-hole pitot tube. Under combustion conditions, the ratio of the two isothermal swirl numbers remains constant for all excess combustion-air levels less than 25%.

The calculated swirl numbers for the isothermal flow field, which is the usual comparison base, were 0.26 and 0.51 for the low- and high-swirl flames respectively. It has been reported(2) that an isothermal-swirl number of 0.6 is the level above which a recirculation core exists for cylindrical quarls. In the case of an expanding conical quarl of the type used in these experiments, the recirculation core occurs at lower swirl numbers.

Flame Appearance

Each fuel was burnt under the two swirl conditions described above at nominal excess-air levels of 5%, 15% and 25%. The deviation from the nominal oxygen content in the flue gases was less than 0.2% in all trials.

The appearances of the low- and high-swirl flames were noticeably different and could be recognized easily by viewing each flame along the axis of the tunnel furnace from the observation port shown in Figure 3.

The low-swirl flames were long and thin, with a luminous orange core which darkened progressively as the excess-air level decreased. They produced only limited heating of the quarl and exhibited a significant buoyancy effect during the early stages of flame development. On the other hand, the high-swirl flames were short and wide with a transparent conical core surrounded by a bright yellow annulus. These flames, which heated the quarl to over 875°C, were symmetrical even at the lowest excess-air level when the central core tended to darken slightly due to a reverse flow of soot and unburnt fuel back to the plane of the oil nozzle.

In general, the high-swirl flames, having a high degree of internal recirculation, were easily ignited and highly stable. The low-swirl flames, which entrain cool flue gas by external recirculation, were easily ignited but were slightly unstable when flame probes were inserted across the quarl exit. It was essential, therefore, that

a) all flame probes at Station 1 be removed before taking performance measurements, and

b) traversing at Station 1 be restricted to the radius between the probe door and the furnace centre line.

Flame Characteristics

Profiles of velocity, temperature and flue gas pollutant composition were measured across each of the various flames at two axial furnace locations. These measurements were made across a horizontal radius of the furnace at 7.5 cm intervals at Station 1 and across a

horizontal diameter of the furnace at 15 cm intervals at Station 2. The measurements at Station 1 were representative of internal flame conditions whereas measurements at Station 2 were representative of conditions in the immediate post-flame gases.

Internal Flame Characteristics

Figures 4 and 5, which are representative of the total experimental data, show that the internal flame profiles of temperature, velocity and gas composition follow two distinctive patterns that are primarily controlled by the swirl number. Fuel quality and the excess-air level affected the overall distribution patterns only marginally.

At the high-swirl condition, all flame velocity profiles showed the presence of the same flow fields as described by the isothermal measurements. The twin peaks in the temperature, velocity, carbon monoxide and oxygen profiles were evident and, as expected, the carbon dioxide profile was the reverse of the oxygen profile. The peaks of velocity and oxygen concentrations were approximately coincident but the peak carbon monoxide concentration was located further from the flame axis than the oxygen peak.

For all fuels, the core of the high-swirl flame was identified as a region of low temperature, reverse flow and complete combustion. This region of complete combustion, which is shown by the CO and O_2 profiles, diminished in size as the excess-air level decreased.

The velocity profiles for No. 2 oil and the SD oil were essentially the same but those for the ND oil and the No. 6 oil showed small differences in that higher reverse velocities prevailed in the core. This suggests that combustion was still occurring in the core downstream of Station 1 and that the lowest rate of combustion occurred with No. 6 oil.

At the low-swirl conditions, the velocity profiles again confirmed that the flow field within the flame was representative of the isothermal measurements. Axially coincident peaks of forward velocity, temperature, oxygen and carbon monoxide concentration were generally present. However, the usual pattern of peak oxygen and minimum carbon dioxide concentration did not occur due to the high carbon monoxide concentrations over large regions of the flame core. This was particularly noticeable with No. 6 oil where carbon monoxide concentrations over 1% and oxygen concentrations below 2% extended over 50% of the furnace diameter. Flames from the other fuels, although showing the same high levels of carbon monoxide over the same furnace section, contained zones in which the carbon monoxide concentration fell below 1% and the oxygen concentration increased to its maximum level.

Minor peaks were recorded on the shoulders of the low-swirl velocity profile for No. 6 oil. This is explained by its low fuel volatility which allows oil droplets from the edge of the fuel spray to migrate across the main axial velocity zone before combustion is initiated. Invariably, excessive smoke production results if these burning droplets impinge on cold furnace surfaces. The other three fuels, with a higher volatility and lower injection velocity, vapourized completely within the axial flow region. Therefore, they did not exhibit a velocity profile anomaly.

Post Flame Characteristics

Typical temperature, velocity and concentration profiles, which were measured immediately downstream of the flame at Station 2, are shown in Figures 6 and 7. It is evident from these curves that a plug-flow regime existed at this furnace location regardless of the fuel burned and the flame conditions. The gas concentration profiles for all fuels were relatively flat, although

those from the high-swirl flames showed traces of air leakage along the measuring slot in the furnace wall. Combustion is essentially complete at this downstream location, although low concentrations of carbon monoxide persisted at the 15% excess-air level for the low-swirl, No. 6 oil flame and at the 5% excess-air level for all of the other flames.

The temperature profiles show that the low-swirl flames consistently produced hotter, more uniform post-flame gases than the high-swirl flames. This is consistent with observations of visible radiation from the flames.

Heat Transfer from the Flames

The axial distribution of heat transfer from the flames was calculated from measurements of the coolant flow and temperature rise in each of the 15 cm calorimetric sections of the tunnel furnace. Typical results are illustrated in Figure 8 where the total heat flux to each calorimetric section was normalized with respect to the maximum heat-flux measurement. By using the peak heat-flux measurement from No. 6 oil as unity, the heat-transfer characteristics for all fuels can be easily compared.

With all of the high-swirl flames, a well-defined peak heat-transfer rate was measured about 30 cm downstream of the burner in a zone where maximum gas velocities and maximum CO_2 concentrations occurred close to the furnace wall. Therefore, this heat transfer peak can be attributed to the combined effects of both convection and radiation in the early stages of the high-swirl flames.

In the case of the low-swirl flames, the peak transfer rates were significantly lower than for the high-swirl flames. Except for No. 6 oil, this peak occurred about 60 cm downstream of the burner quarl, indicating a general decrease in combustion rates with swirl intensity.

Figure 9, which is representative of all the fuels, shows that the high-swirl flames produced a higher heat-transfer rate than the low-swirl flames in the first 150 cm of the furnace. Beyond this position the pattern was reversed with the heat transfer from the low-swirl flames exceeding that from the high-swirl flames. The temperature profiles at Station 2 confirmed that the heat transfer from the low-swirl flame had been reduced during the early stages of combustion.

The total heat transfer to the tunnel furnace was calculated from the combustion products, flue gas temperature and mass flow rate, as shown in Table 2. The heat transfer to the furnace increased with decreasing excess-air level and was consistently higher for the high-swirl flames than for the low-swirl flames. For any given flame condition, the total heat-transfer rates from the No. 2 oil, SD oil and ND oil were essentially constant while those from No. 6 oil were generally lower by about 5% at high excess-air levels. This effect was clearly due to the higher C:H ratio of the No. 6 oil demanding a larger mass of air to achieve any specific excess-oxygen level.

The local heat-transfer rates, as measured at Stations 1 and 2 with the IFRF heat flux probe, emphasize the difference between low- and high-swirl flames. At Station 1 the low-swirl flames gave heat transfer rates that were consistently 50% less than those shown by the high-swirl flames, whereas at Station 2 this trend was reversed as shown in Table 3. The calorimetric heat transfer rates, illustrated in Figure 8 , were confirmed by this alternative series of measurements.

TABLE 2

Total Heat Transfer in the Tunnel Furnace

Fuel	Degree of Swirl	Nominal Excess-Air Level, %	Heat Transfer to Tunnel Furnace as % of Input
No. 2 Oil	Low	5 15 25	71.2 70.0 67.7
	High	5 15 25	78.3 76.0 73.2
SD Oil	Low	5 15 25	73.8 71.8 68.5
	High	5 15 25	76.9 75.0 74.1
ND Oil	Low	5 15 25	72.8 70.7 68.5
	High	5 15 25	76.1 75.1 73.3
No. 6 Oil	Low	5 15 25	71.1 67.6 63.6
	High	5 15 25	75.5 73.1 75.5

TABLE 3

Heat Transfer Rates
(Measured with the IFRF Heat Flux Probe)

Fuel	Degree of Swirl	Nominal Excess-Air Level %	Heat Flux W/m²	
			Station 1	Station 2
No. 2 Oil	Low	5	44,200	30,000
		15	41,000	33,100
		25	42,600	26,800
	High	5	61,500	15,800
		15		15,000
		25	52,100	15,800
SD Oil	Low	5	25,200	33,100
		15	34,700	31,600
		25		33,100
	High	5	52,100	23,700
		15	61,500	25,200
		25	48,900	20,500
ND Oil	Low	5	33,100	41,000
		15	30,000	36,300
		25	28,400	34,800
	High	5	47,300	25,200
		15	56,800	25,200
		25	80,400	33,100
No. 6 Oil	Low	5		
		15	48,900	36,300
		25	53,600	37,900
	High	5	42,600	28,400
		15	69,400	15,800
		25	64,700	

Combustion Efficiency

Solids Loading

The solids loading in the gas steam was measured using a sampling methodology developed at CCRL. The solids loadings, given in Table 4, show that all fuels except No. 6 oil can be burnt at both swirl conditions with medium and high excess-air levels without exceeding a solids loading of 0.01 mg/m^3. This solids loading was exceeded only with No. 6 oil at all excess-air levels and both swirl conditions, and with ND oil at the low excess-air, low-swirl condition.

Carbon Monoxide

The carbon monoxide concentrations in the exhaust gases, given in Table 4, were below 1000 ppm (0.1%) in all cases. All fuels showed an increase in carbon monoxide as the excess-air level was decreased. The low-swirl flames generally produced more carbon monoxide than the high-swirl flames, although this difference became less marked as the excess-air level increased. The ratio of carbon monoxide from the low-swirl flame to that from the high-swirl flame had average values for all the fuels of 9.9, 3.6 and 1.4 at excess-air levels of 5%, 15% and 25% respectively.

Gaseous Hydrocarbons

None of the flames produced significant quantities of gaseous hydrocarbons. On one occasion a concentration of 5 ppm was detected but generally only trace quantities (1 ppm) were recorded.

Smoke Opacity

Smoke opacity was measured by a Bacharach smoke meter which gives an indication of changes in smoke opacity at Ringelman numbers below 1. The Bacharach scale registers from 0 to 9 with the maximum value of 9 being approximately equivalent to a Ringelman number of unity

TABLE 4

Combustion Performance Data

Fuel Oil	Fuel Pre-Heat Temp °C	Thermal Input MJ/sec or MW	Degree of Flame Swirl	Nominal Excess Air Level %	Gas Analysis						Flue Gas Exit Temp °C	Bacharach Smoke Number	Parti-culate Loading µg/Nm³
					O_2 %	CO_2 %	CO ppm	NO ppm	C_xH_y ppm	SO_2 ppm			
No. 2	21	0.525	Low	5	1.1	14.0	37	32	0	111	615	4	2.3
				15	3.1	13.8	31	39	0	104	593	4	4.6
				25	5.2	12.7	24	52	1	95	593	1	2.3
			High	5	1.2	15.0	110	49	0	112	477	9	4.6
				15	3.1	13.6	44	59	0	106	488	2	9.1
				25	5.0	12.6	16	39	0	98	504	1	4.6
SD	21	0.545	Low	5	1.2	14.3	300	52	5	95	596	9	6.9
				15	2.9	13.8	80	76	0	86	594	4	4.6
				25	5.0	12.4	29	101	1	83	616	5	4.6
			High	5	1.0	15.1	26	125	0	91	532	1	6.9
				15	3.0	13.8	12	94	0	88	535	0	4.6
				25	5.1	12.0	17	107	0	82	299	0	2.3
ND	38	0.548	Low	5	1.0	14.8	812	48	0	505	609	7	13.7
				15	2.9	13.4	34	73	1	466	611	3	4.6
				25	4.9	11.0	15	82	0	456	618	0	2.3
			High	5	1.0	14.8	30	97	0	491	543	4	2.3
				15	3.0	13.4	14	101	0	414	528	0	4.6
				25	5.1	12.6	13	100	0	444	527	0	2.3
No. 6	105	0.521	Low	5	1.1	15.6	340	137	0	1161	593	7	32.0
				15	2.9	13.8	322	138	0	1276	619	8	13.7
				25	5.0	12.6	149	173	1	1195	629	5	22.9
			High	5	1.2		426	175	0	1354	518	9	34.3
				15	3.0	13.8	68	240	0	1223	5[illegible]	0	13.[illegible]
				25	5.5	12.2	67	279	0	1188	563	0	18.3

TABLE 5

Nitric Oxide Emissions

Fuel	Degree of Swirl	Nominal Excess-Air Level, %	Nitric Oxide Emissions g/kg Fuel
No. 2 Oil	Low	5	0.51
		15	0.68
		25	0.98
	High	5	0.74
		15	1.03
		25	0.78
SD Oil	Low	5	0.85
		15	1.35
		25	1.95
	High	5	2.04
		15	1.67
		25	2.06
ND Oil	Low	5	0.79
		15	1.30
		25	1.58
	High	5	1.59
		15	1.79
		25	1.93
No. 6 Oil	Low	5	1.76
		15	2.34
		25	2.32
	High	5	2.78
		15	4.15
		25	5.36

Decreases in smoke opacity occurred with (a) increases in excess-air, (b) increases in swirl number and (c) improvement in fuel quality. As could be expected, the highest Bacharach smoke number, which was below a No. 9 at all times, was obtained with the low-swirl No. 6 oil flame at the lowest excess-air level.

Nitric Oxide Emissions

From Table 5 it is evident that the levels of nitric oxide emissions from all four fuel oils were primarily controlled by the nitrogen content of the fuel and the degree of flame swirl.

Typically, the lowest NO emissions were associated with the low-swirl flames, the lowest nitrogen fuels, the lowest excess-air level and the highest CO emissions. With the high-swirl flames, decreases in NO emissions occurred with decreases in excess-air for only the ND oil and No. 6 oil.

Sulphur Dioxide Emissions

The sulphur dioxide concentrations in the flue gases reflect the sulphur contents of the fuels and the excess-air levels as shown in Table 4.

APPRAISAL OF LIQUID ALTERNATIVES

1. Both the synthetic and the natural crude oil derivatives are acceptable substitutes for No. 2 oil, when evaluated with respect to combustion efficiency, furnace heat-transfer rates and pollutant emissions. These characteristics were essentially constant for all three fuels at any given burner swirl and excess-combustion-air condition. The synthetic derivative can be burned without preheat, but the natural derivative with a pour point of 27°C required preheating to 38°C for good pumpability and atomization using conventional No. 2 oil equipment

2. Under low-swirl conditions the No. 6 oil, because of its high C:H ratio and low volatility, yielded higher furnace heat-transfer rates but slightly lower combustion efficiencies than the three higher quality fuels. However, under high-swirl conditions, the heat-transfer rates and combustion efficiencies were the same for all four fuels.

3. In cases where No. 2 and No. 6 oil are already used on an interchangeable basis, then either the synthetic or the natural crude oil derivative will be equally satisfactory substitutes.

4. Swirl intensity was effective in controlling flame stability and flame geometry. The high-swirl number produced short wide flames having high heat-transfer rates close to the burner, whereas the low-swirl number produced long thin flames having appreciably lower heat-transfer rates close to the burner. In general, the combustion efficiency of a flame can be improved by increasing the swirl number, but it is important to note that over-swirling can cause flame impingement on furnace walls with a subsequent deterioration in the degree of burn-out.

5. With all fuels, NO emissions were decreased by decreases in (a) fuel nitrogen, (b) swirl intensity and (c) excess-combustion-air levels.

COLLOIDAL ALTERNATIVES TO CONVENTIONAL LIQUID FUELS

Despite the several references[3,4,5] to use of coal-in-oil suspensions dating back to the early part of this century, there is little quantitative information on the combustion performance of these fuels. Typical of the early reports on the use of "colloidal fuel" is one describing experiments on board the USS Gem[6] where "stimulated by the inventiveness of war it (colloidal fuel) .....was so successful that the Gem was worked from April to July 1918 solely on this fuel with results satisfactory in every respect". This recommendation is enthusiastic but scanning of eye-witness reports shows that the operating time during the test period was accumulated in short bursts of approximately one hour duration, during which time no effective boiler measurements could be made. In addition, the completeness of combustion and the control of stack emissions were not matters of significant concern.

Presently, coal-in-oil fuels are attracting considerable attention because a continuing shortfall of industrial fuel oil is anticipated and it is essential that a suitable substitute be available for use in conventional oil-fired equipment. Accordingly, the main objectives of this study were:

1. To clarify the major parameters that affect the physico-chemical properties of coal-in-oil suspensions.
2. To evaluate the combustion and pollution characteristics of selected coal-in-oil blends.
3. To assess the suitability of commercially available hardware for preparing, handling and burning coal-in-oil fuels.

Handling of Coal-in-Oil Suspensions

The mixtures most commonly used in previous experiments contained 35%-45% by weight of coal. It has been observed that the apparent viscosity of colloidal fuel increases sharply with increased solids concentration [7]. Figure 10 shows that this will be dependent on the size distribution of the coal but for normal pulverized-coal size distributions it appears that a 40% coal concentration is the maximum acceptable level.

Extensive experiments conducted by the Research Council of Alberta[8] show that up to 72% coal (wt/wt.) can be added to oil and still give a pumpable fluid. They also noted that particle attrition occurs rapidly in the handling of the suspension to give an equilibrium size distribution. This attrition was thought to occur in the pumps since samples taken diametrically across a pipeline showed a preferential increase in the solids loading within the central core leaving the outer annulus depleted in solids.

The Alberta pipelining experiments demonstrated that slurry viscosities calculated by the Poiseulle equation were all lower than laboratory data obtained with a Brookfield viscometer. The pipeline experiments also showed that colloidal fuels behaved as Newtonian fluids below 50% (wt/wt) rather than below 10% (wt/wt) as indicated by viscosity studies. This was attributed to the distribution of solids across the pipeline diameter which effectively reduced flow resistance.

The Stability of Coal-in-Oil Suspensions

The oleophilic nature of the coal particles affects the long-term stability of coal-in-oil suspensions. Particles without surface polar groups reject contact with the oil (poor "wettability") and settle quickly giving a hard sediment that is difficult to re-entrain. Coke and

highly-oxidized coals fall into this category. The absence of polar groups can, to some extent, be offset by the addition of small amounts (2% by weight) of polar liquids such as water, tannic acid or varsol to the coal; highly stable suspensions can also be obtained with commercial dispersants. The amounts of polar liquids and dispersants required for satisfactory stability can only be determined by experiment.

Lignitic coals are usually easy to blend and stabilize in oil because their cellulosic constitutents are oleophilic.

Coal-in-Oil Combustion Experiments

Coal Quality and Preparation

The coals used in the preliminary combustion trials were a western Canadian lignite known as Bienfait and rejects of an eastern Canadian bituminous coal known as Dominion. Because the bituminous coal was a washery reject it contained more than 60% inert fusinite and semi-fusinite, both of which profoundly restricted ignition and combustion.

TABLE 6

Proximate Analyses of the Coal Components of the Coal-in-Oil Fuels

		Bienfait	Dominion
Moisture	%	21	1
Ash	%	8 5	.9
Volatile Matter	%	32	25
Fixed Carbon	%	38	64
Sulphur	%	0.5	1
Gross Calorific Value	kJ/kg	19,790	32,590

The size distributions of the pulverized coals are shown in Table 2; these coals were subsequently used in the preparation of the fuels for the combustion trials.

TABLE 7

Size Distributions of the Coal Components of the Coal-in-Oil Fuels

Screen Fraction	Bienfait Lignite	Dominion Bituminous		
		Grind A	Grind B	Grind C
plus 60	0.63	0.59	2.11	2.85
60 to 100	0.54	0.53	11.29	21.27
100 to 140	0.63	0.89	8.35	14.55
140 to 200	1.21	3.81	6.85	11.03
200 to 325	12.04	15.49	11.92	14.78
minus 325	84.95	78.68	59.48	35.52

The gross calorific values of the coal-in-oil fuels were:

Bienfait Coal-in-Oil	37,250	kJ/kg
Dominion Coal-in-Oil	40,740	kJ/kg

Coal-in-Oil Stability

A series of static sedimentation tests were done on the Dominion coal in No. 2 oil (33% coal by weight). Typical results are shown in Figure 11 where the influence of the larger size particles on the rate of settling is clearly demonstrated. In view of these settling characteristics, coal Grind "C" was eliminated from the combustion experiments and it was decided to provide continuous stirring and circulation of all coal-in-oil blends rather than to use a stabilizing agent to minimize fuel separation in the

storage tank. Experimental tests were limited to four hours by the capacity of the laboratory bulk-storage tank.

The Fuel-Supply System

The fuel-handling system, illustrated in Figure 12, was designed to operate at a minimum flow velocity of 45 cm/s with the coal-in-oil mix being circulated around the closed-loop system by a Moyno positive-displacement pump. The pressure drop in the flow line to the burner was approximately 15 cm water column per 100 m of line. This compares with values of 3.2 cm water column per 100 m of line reported by Berkowitz[7] and the difference is attributed to the different coal sizes. No major change in this pressure drop was observed during any of the combustion experiments.

The Coal-in-Oil Burner

The burner used in the combustion studies was a low-pressure atomizing type that is illustrated in Figure 13. In this system, the primary air is divided by movement of the axially adjustable cone into an inner and an outer air stream. The inner air stream passes around the oil nozzle and aspirates the fuel to produce the primary air-fuel mixture. The oil nozzle is illustrated in Figure 14. The primary air-fuel mixture combines with the outer air stream in the mouth of the fixed cone, Figure 13, where the turbulence generated by the two high-velocity flows breaks up any large liquid fuel droplets that have persisted and generates a homogeneous secondary air-fuel mixture. This mixture ignites within a refractory cone downstream of the burner and the flame front stabilizes within this cone. Provision was made for the injection of secondary air and/or recirculated combustion products just past the conical refractory flame holder.

The coal-in-oil burner and refractory quarl were mounted on a 45 cm diam x 60 cm long refractory-lined combustion chamber at the front end of the tunnel furnace.

Gas and Particulate Sampling and Analyses

Particulate matter was sampled by the system developed at CCRL. A stainless steel probe was inserted into the gas stream to withdraw a sample at isokinetic conditions through a cyclone separator and filter combination for subsequent determinations of the solids burden and the degree of coal burn-out.

Samples were taken from the centre of the flue duct 1 m downstream from the particulate sampling point and continuously analyzed for carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), nitric oxide (NO), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2). Sulphur trioxide (SO_3) measurements were taken intermittently at the same location.

Experimental Data

The velocity profiles measured at the exit plane of the burner indicated that the flow had a dominant axial velocity component. The radial velocity components reflect the effect of the oil nozzle which diverts flow from its axial path. The tangential component of velocity was approximately symmetrical about the centre line of the burner and showed the presence of some rotation in the flow pattern. The proximity of the peaks of tangential velocity to the burner axis indicated that the tangential momentum was small in relation to the axial momentum, this was further illustrated by the calculated value of the swirl number, 0.1. This implies that the burner will not generate a substantial central recirculation core in a flame. Further investigation with a small hammer-head pitot revealed the existence of a small bluff body

recirculation vortex in the immediate wake of the oil nozzle. This vortex did not extend more than 3 cm downstream from the nozzle.

Velocity profiles measured across the mouth of the refractory pre-combustion chamber did not show the existence of any recirculation zone. It was noticed, however, that all the velocity components periodically fluctuated by as much as 50%. This was attributed to the existence of massive eddies in the flow systems. The existence of these eddies undoubtedly contributed to the air-fuel mixing in the flame and to increased turbulence and micro-mixing.

The appearance of the coal-in-oil flame differed from that of a No. 2 oil flame in the downstream regions; the length of the visible flame increased. The bituminous coal-in-oil generated a post-flame gas with a significant carry-over of burning particulate material which was not observed with the lignitic coal-in-oil . In both cases the fuel could be switched between coal-in-oil and oil without any loss of ignition or noticeable change in flame stability.

The experimental conditions and primary results from the combustion experiments are shown in Table 8. These results show that good burn-out of the lignite was achieved without modification to the burner system. The degree of burn-out (>91%) at both excess-air levels was considered satisfactory for an unoptimised lignite flame although a burn-out of 99% can be achieved with the same coal when pulverized and fired in a pilot scale boiler. The results show that the burn-out of the bituminous coal reject was unsatisfactory (<56%) despite the wide variation in combustion conditions.

TABLE 8

Summary of Combustion Trials Identified by Coal Component

Coal Component	Bienfait Lignite		Dominion Bituminous					
Test No.	1	2	3	4	5	6	7	8
Coal Grind			A	A	A	B	B	B
Firing Rate: Kg/hr	68.1	68.1	45.4	45.4	59.0	57.3	50.9	61.8
Proportioning of Air Supply								
Primary	0.38	0.35	1	0.7	0.6	0.77	0.3	0.7
Secondary	0.62	0.65	0	0.3	0.1	0.23	0.3	0.2
Recirculated Flue Gas	0.0	0.0	0	0.0	0.3	0.0	0.4	0.1
Flue Gas Analyses								
O_2 vol %	4.6	2.5	5.0	2.5	2.0	5.0	1.25	5.0
CO_2 vol %	12.3	14.4	12.5	13.5	14.4	12.5	14.8	13.0
CO vol %	0.0	0.0	0.05	0.25	0.0	0.05	0.0	0.05
Extent of Fuel Burn Out								
Total Fuel	0.99	0.96	0.75	0.70	0.78	0.82	0.68	0.80
Oil Component	1	1	1	1	1	1	1	1
Coal Component	0.98	0.91	0.30	0.42	0.39	0.56	0.12	0.44
Trace Gas Analyses								
NO ppm	66	61	114	78	93	75	99	99
SO_2 ppm	171	180	153	180	167	186	225	159
SO_3 ppm	9	34	-	3	2	1.2	1	2
Flue Gas Dust Loading								
mg/Nm^3	103	96	470	377	531	410	666	510

Petrographic examinations revealed that the bituminous coal consisted largely (60%) of fusinite and semi-fusinite which are non-reactive, low-volatile high-density materials. These maceral components were found to persist in an essentially unreacted form in the particulate samples taken downstream in the post-flame gases.

APPRAISAL OF COLLOIDAL ALTERNATIVES

Experience to date indicates clearly that coal-in-oil an acceptable substitute fuel provided that two conditions are met. The first is that an optimum size distribution of the coal should be established for the stability of the suspension, pumpability and satisfactory burn-out at excess-air levels below 10%. The second is that a limit should be established for the fusinite, semi-fusinite and oxidized macerals in the coal.

The unsatisfactory burn-out of the bituminous coal reject in these experiments has been attributed to its maceral structure. It is recommended that petrographic examinations be a routine step in laboratory procedures for selecting coals to ensure that a satisfactory flame and good burn-out of the coal can be achieved with a 33% coal-in-oil slurry.

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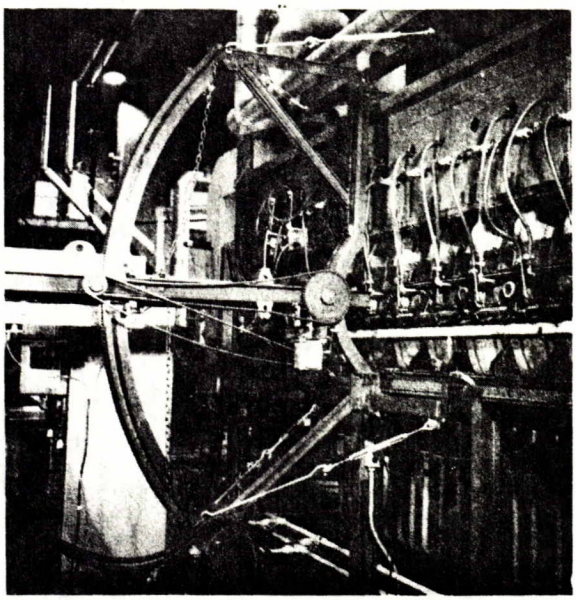


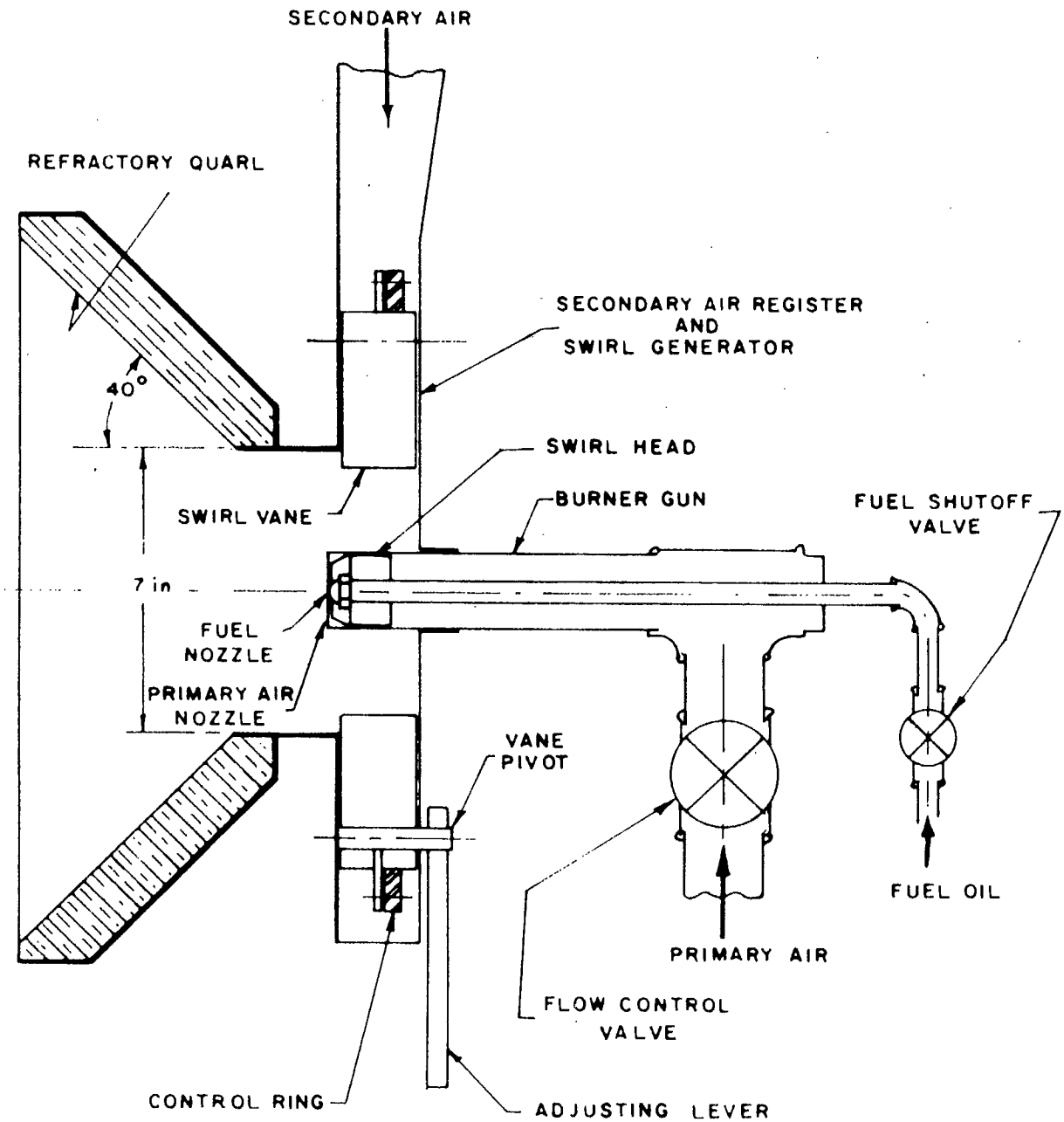


Figure 2 The experimental burner used in the liquid fuel experiments

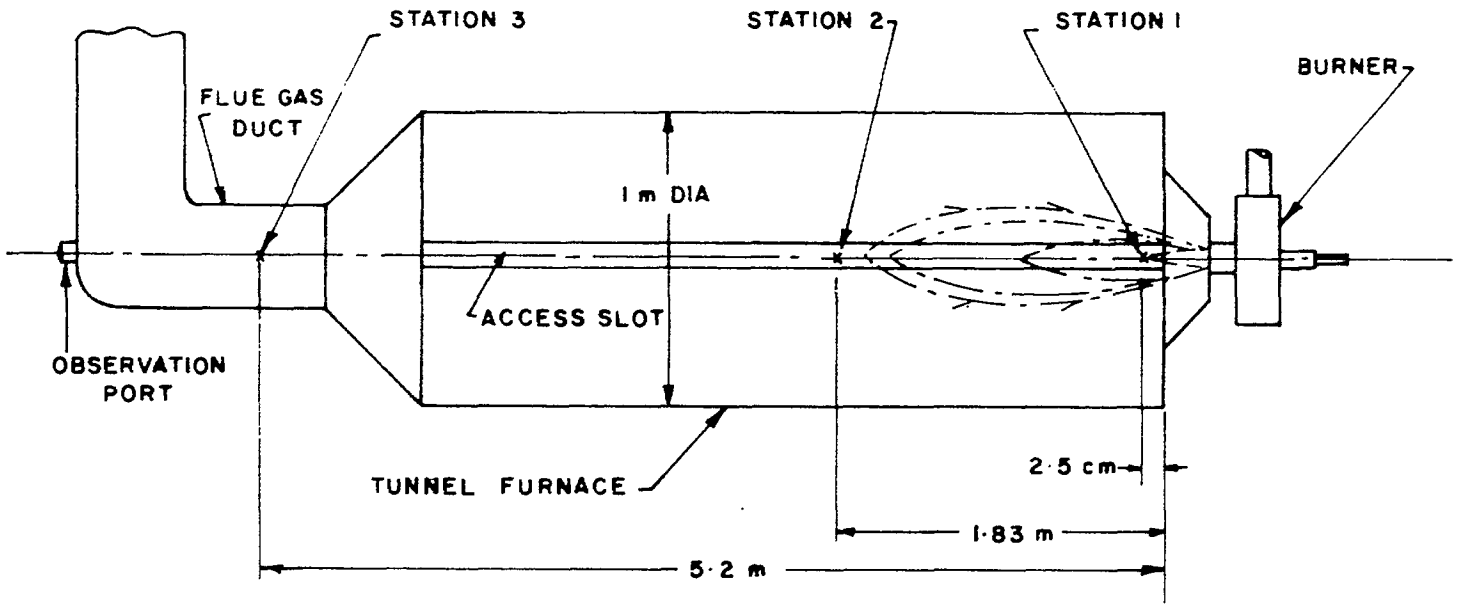


Figure 3 The CCPL tunnel furnace showing the sampling locations used in the liquid fuel experiments.

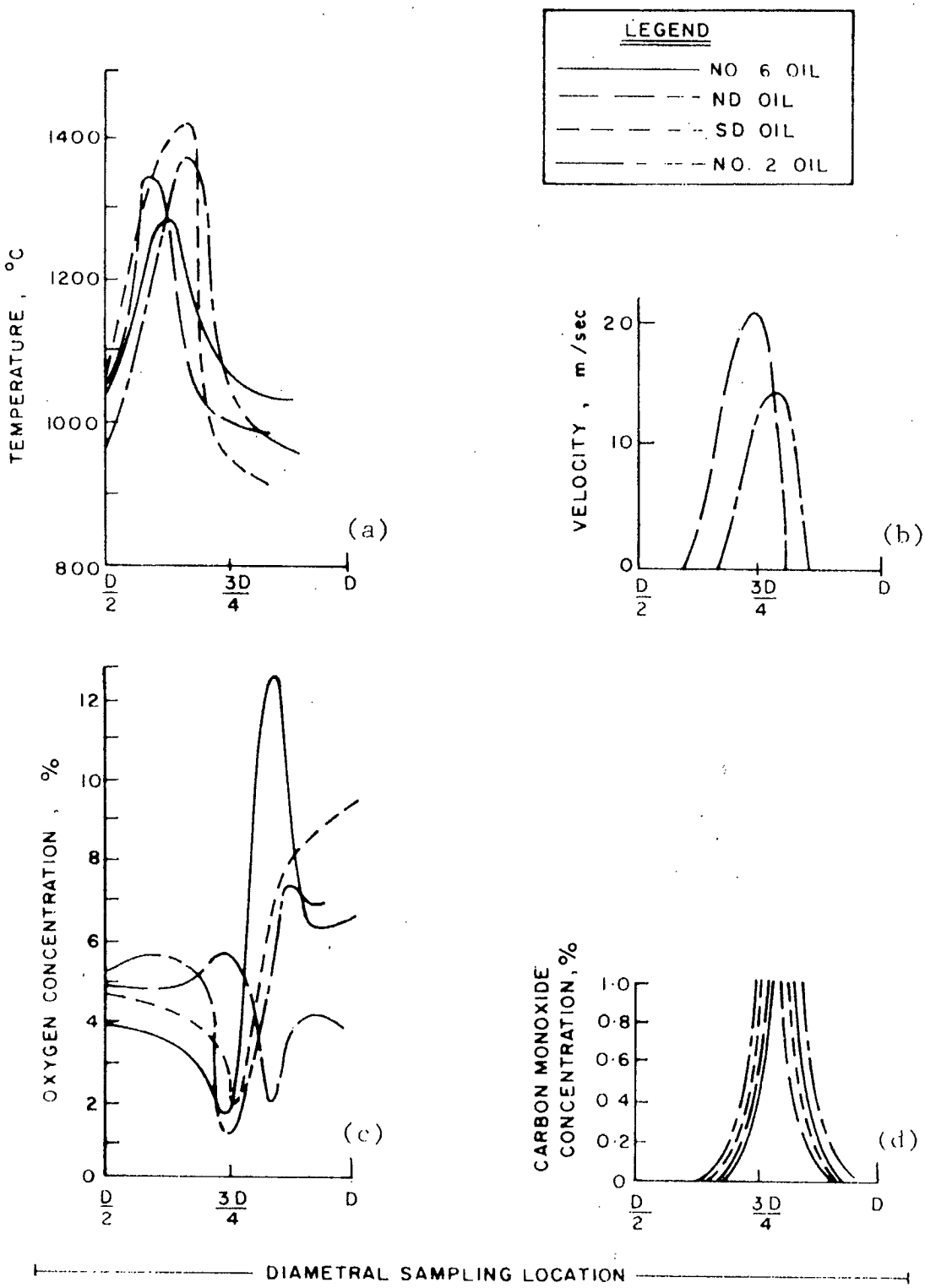


Figure 4. Typical profiles in the high-swirl flame at Station 1, S° 0.

(a) temperature profile
(b) velocity profile
(c) oxygen profile
(d) carbon monoxide profile

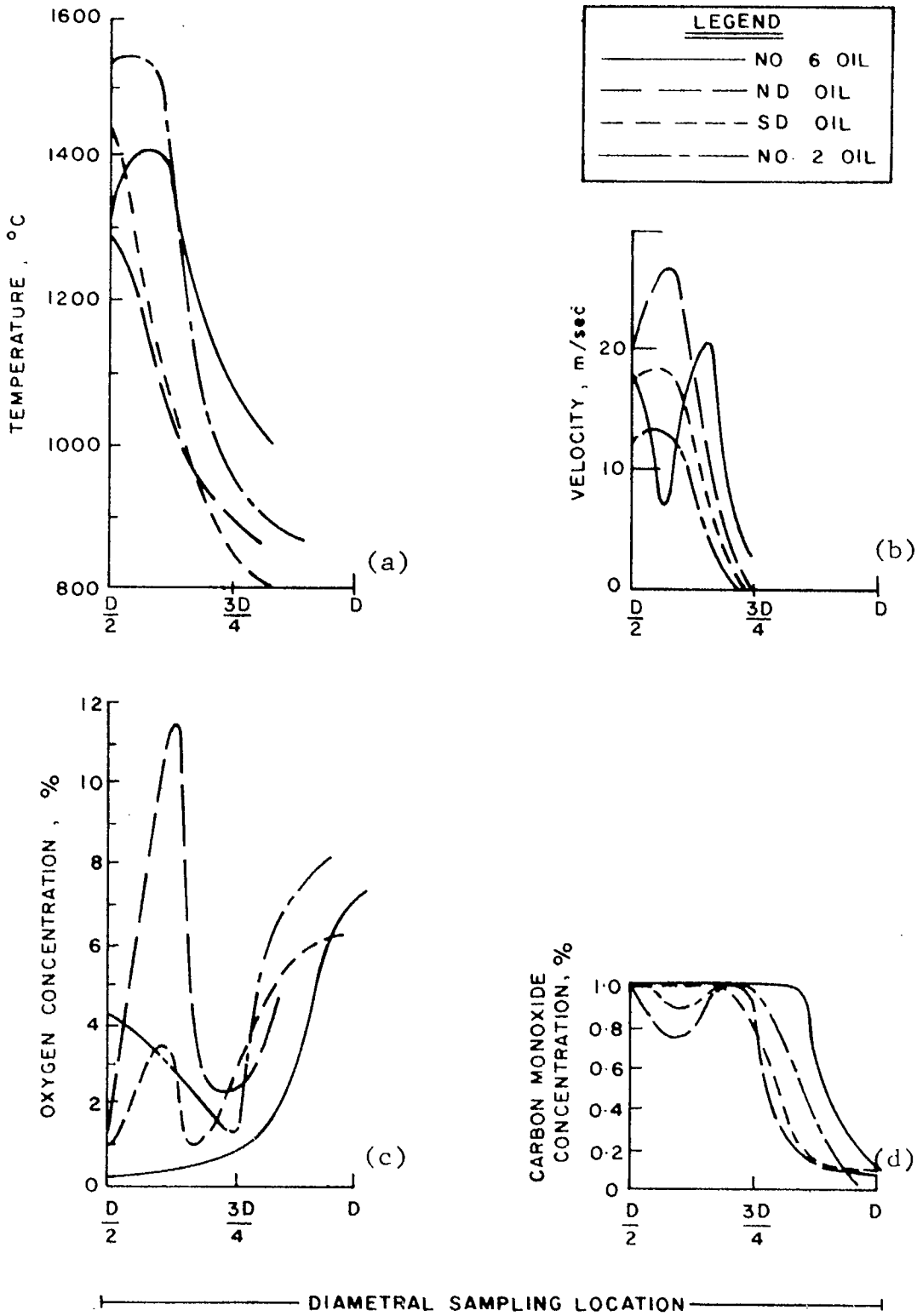


Figure 5. Typical profiles in the low-swirl flame at Station 1; 5% O_2.

(a) temperature profile
(b) velocity profile
(c) oxygen profile
(d) carbon monoxide profile

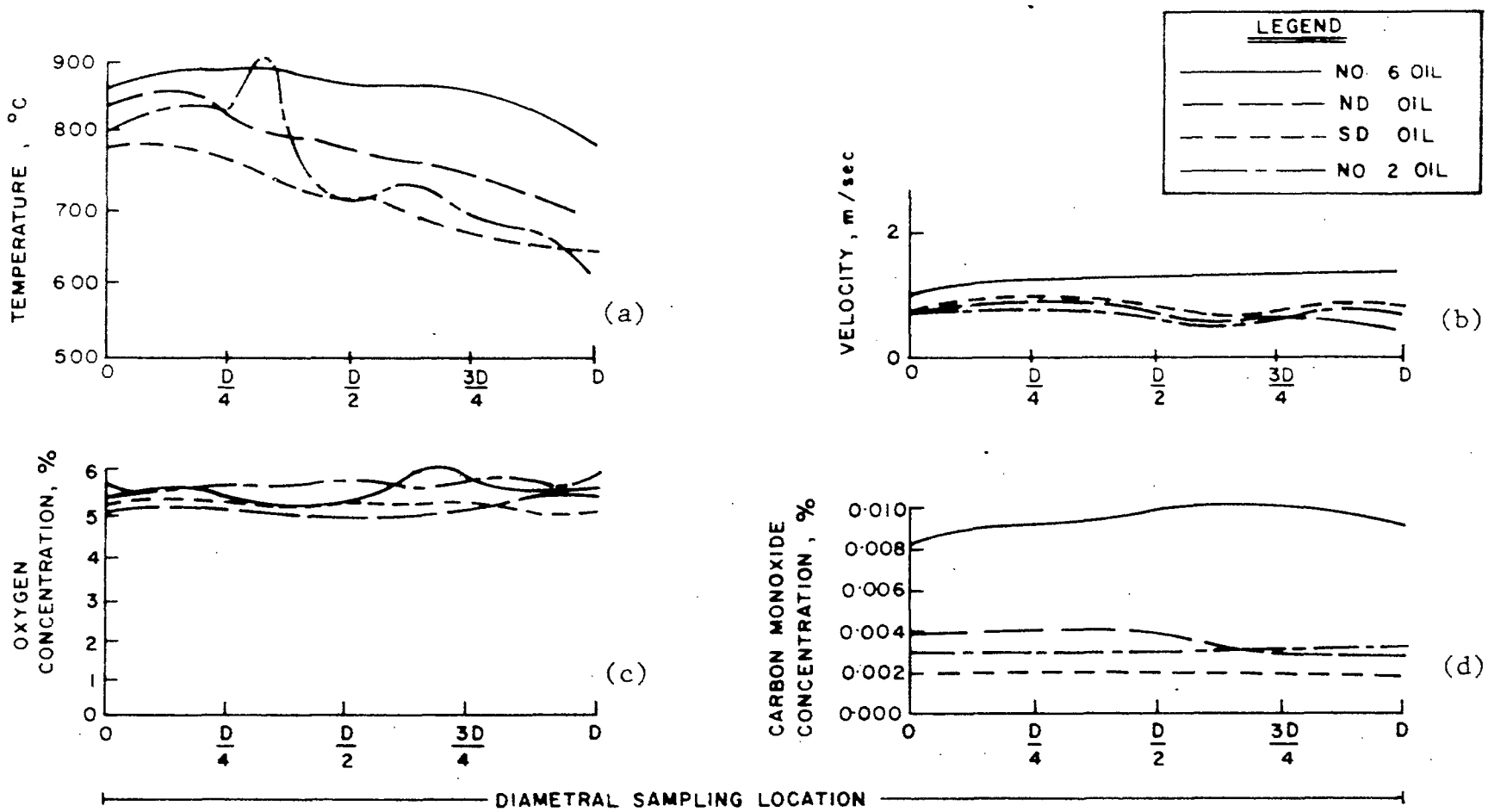


Figure 6. Typical profiles in the post-flame gases at Station 2; high-swirl flame with 5% O_2.
(a) temperature profile
(b) velocity profile
(c) oxygen profile
(d) carbon monoxide profile

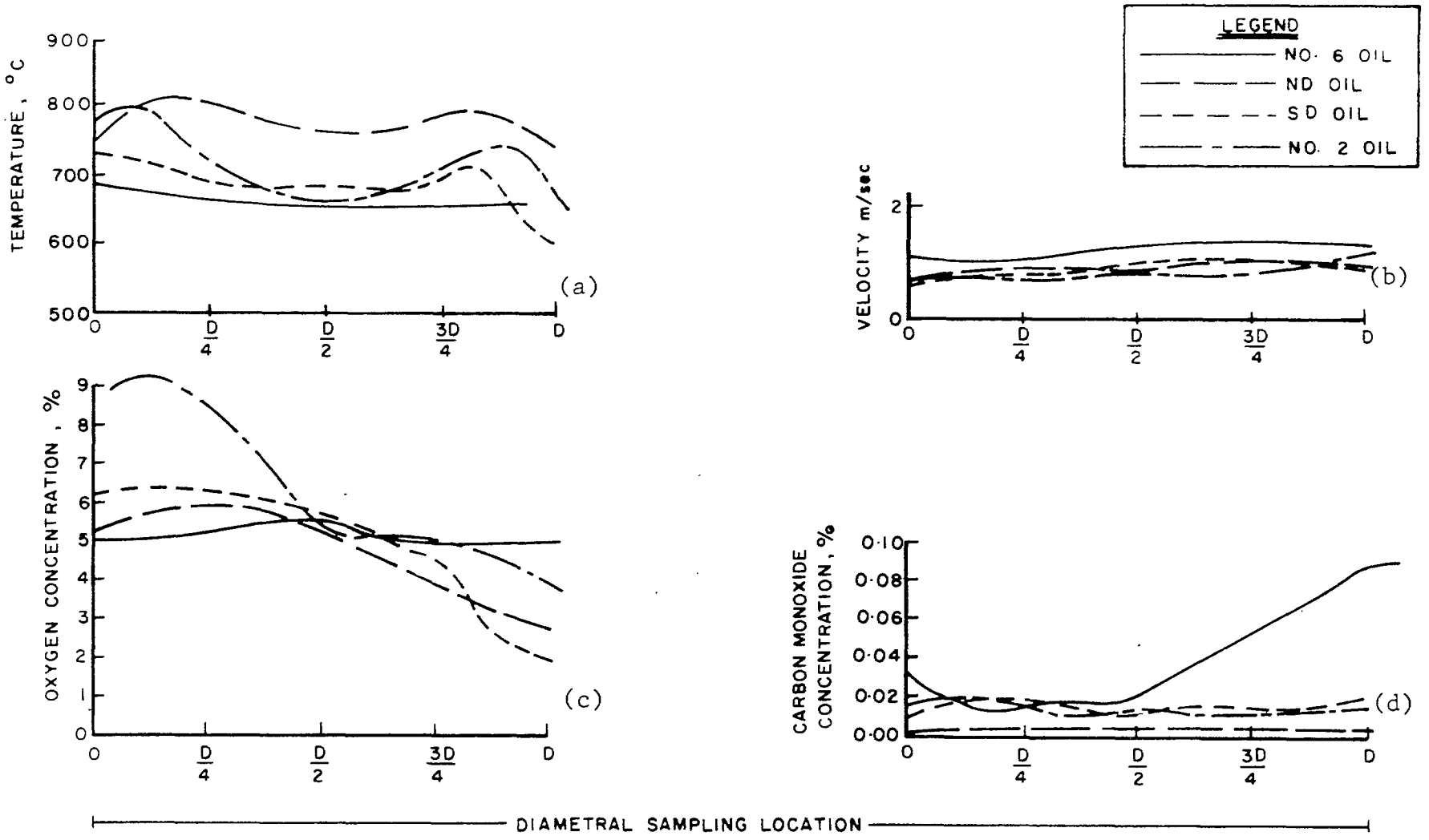
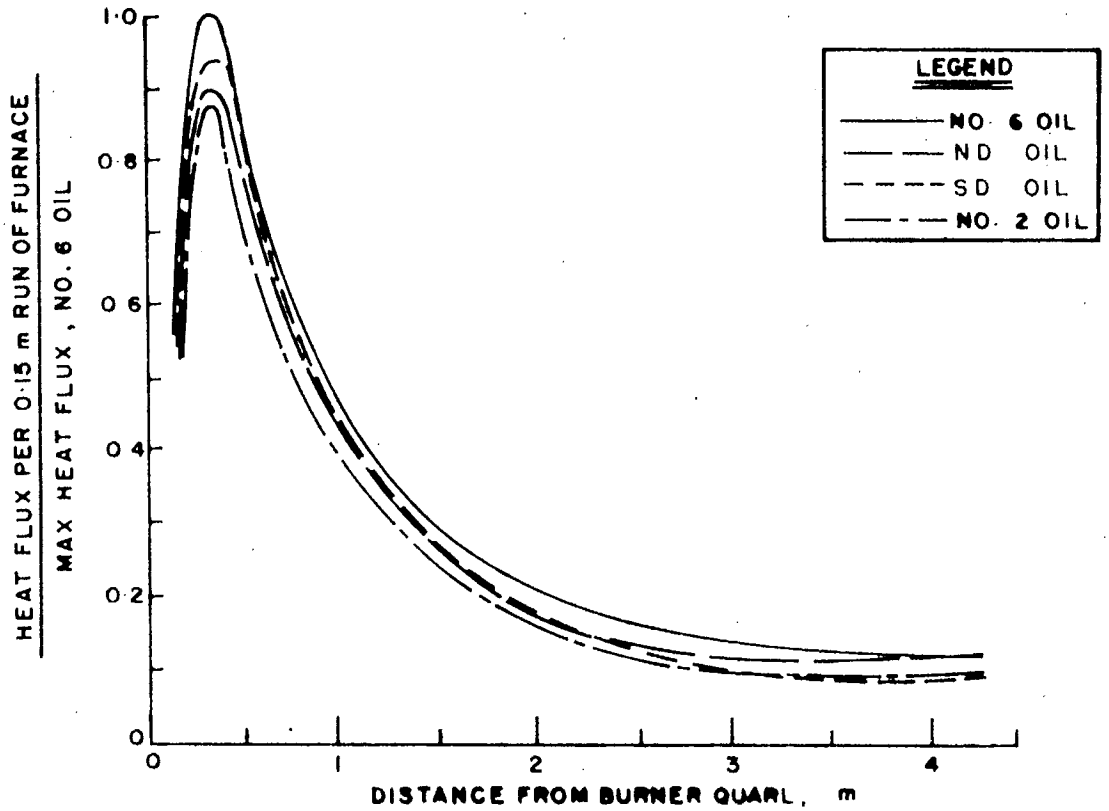
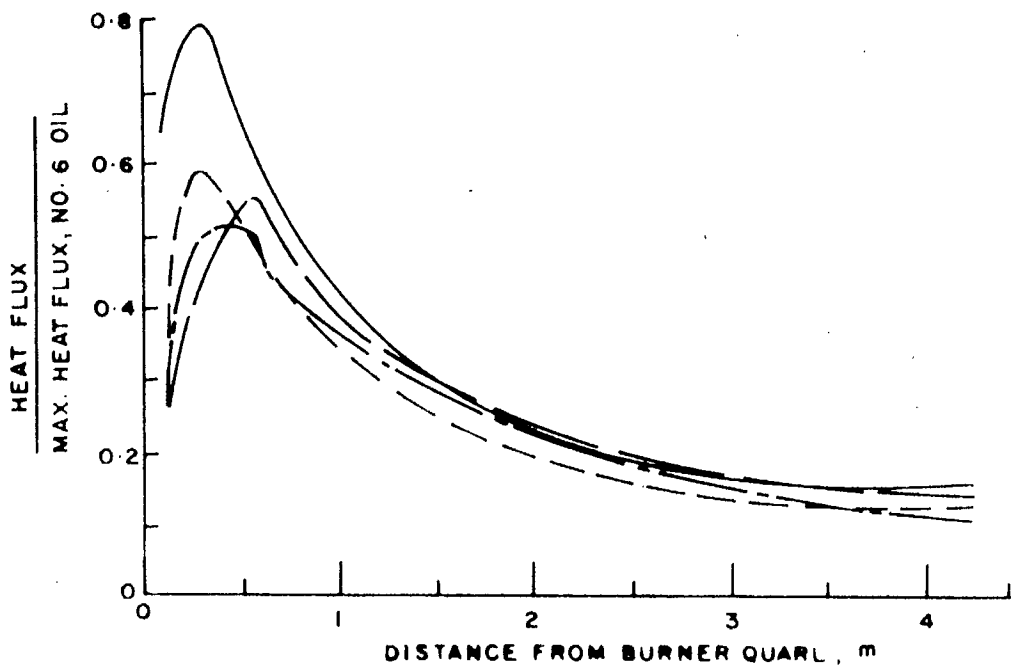


Figure 7. Typical profiles in the post-flame gases at Station 2: low-swirl flame with 5% O_2.

(a) temperature profile
(b) velocity profile
(c) oxygen profile
(d) carbon monoxide profile



(a)



(b)

Figure 8 Typical patterns of heat transfer distribution along the furnace.

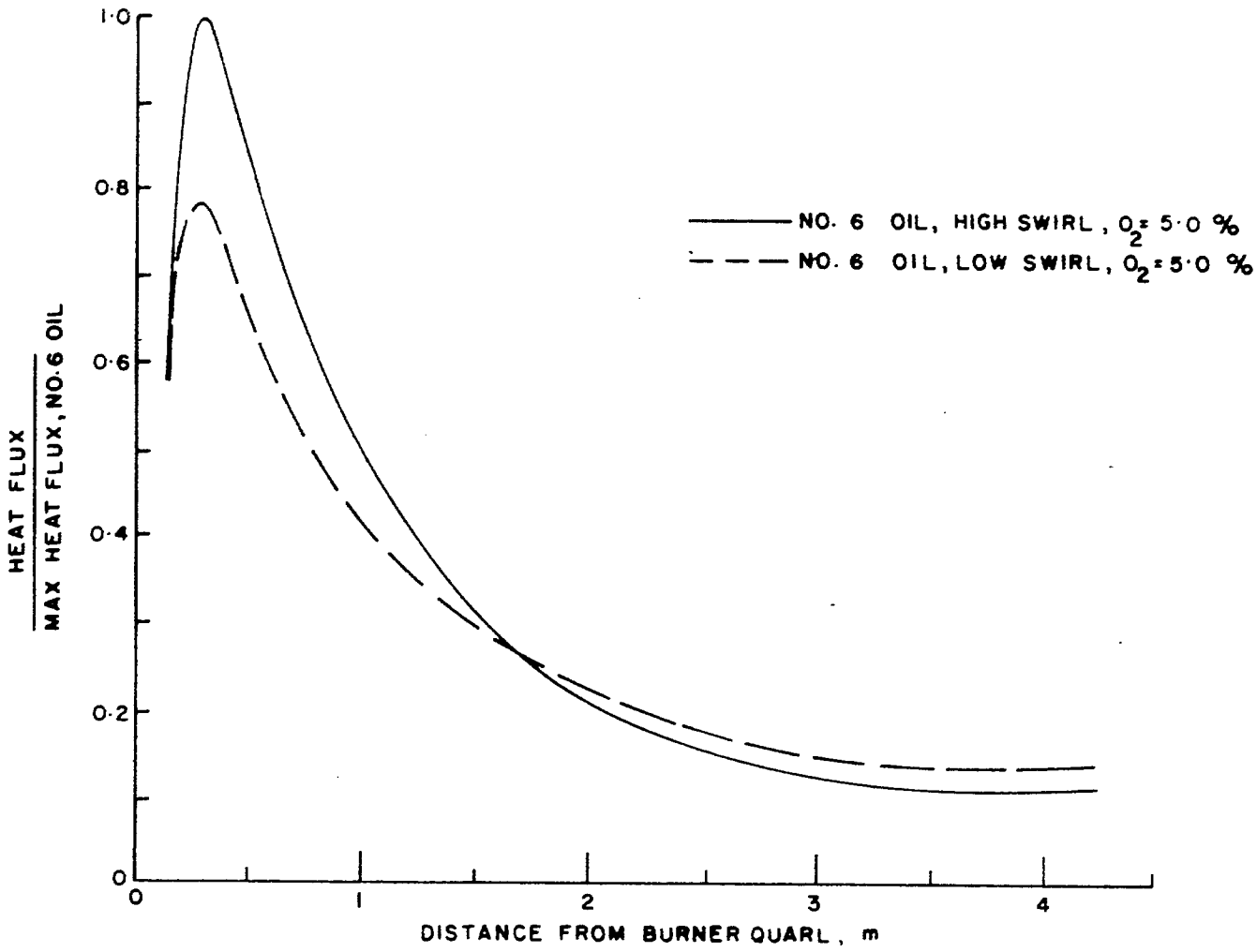


Figure 9. A comparison of heat transfer distribution along the furnace from a high- and low-swirl flame. (No 6 oil at 5% O_2 in the flue gases)

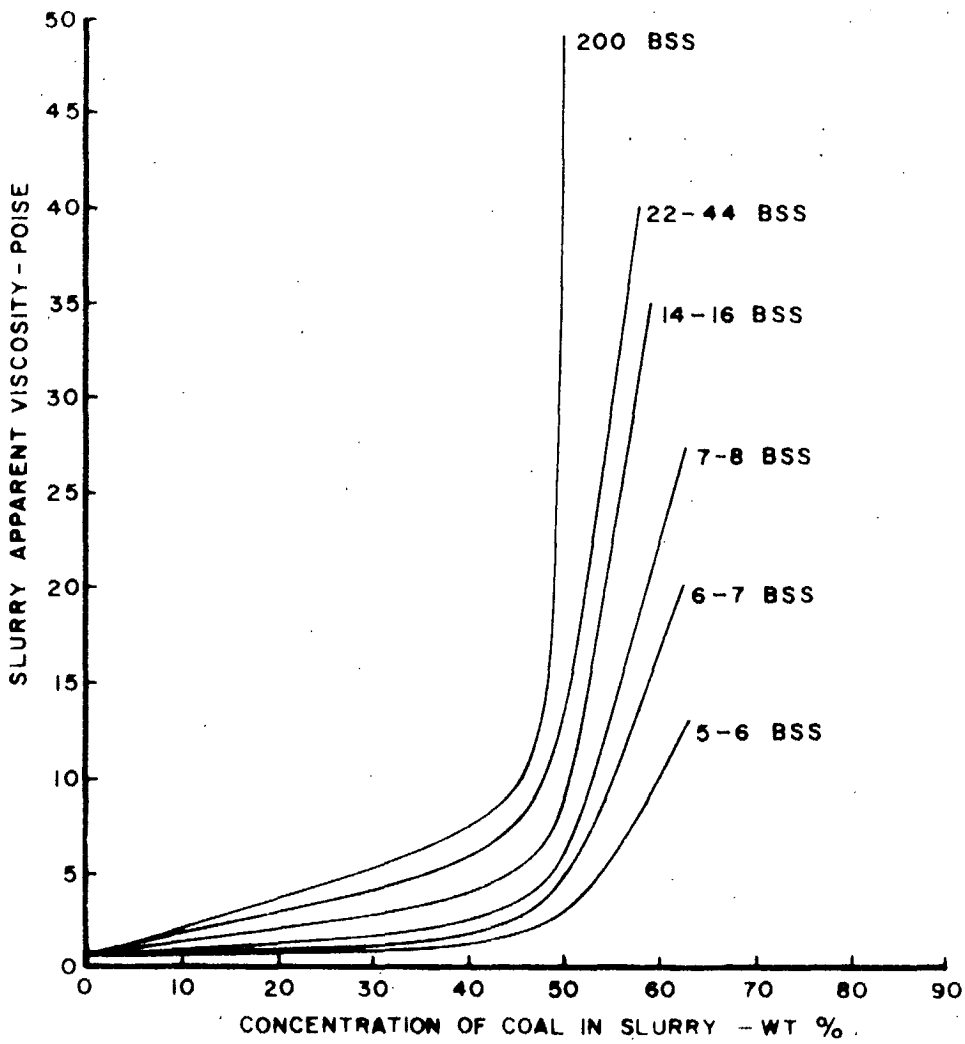


Figure 10. The effect of coal particle size on slurry apparent viscosity at °C.

(after Whittingham and Wenger)

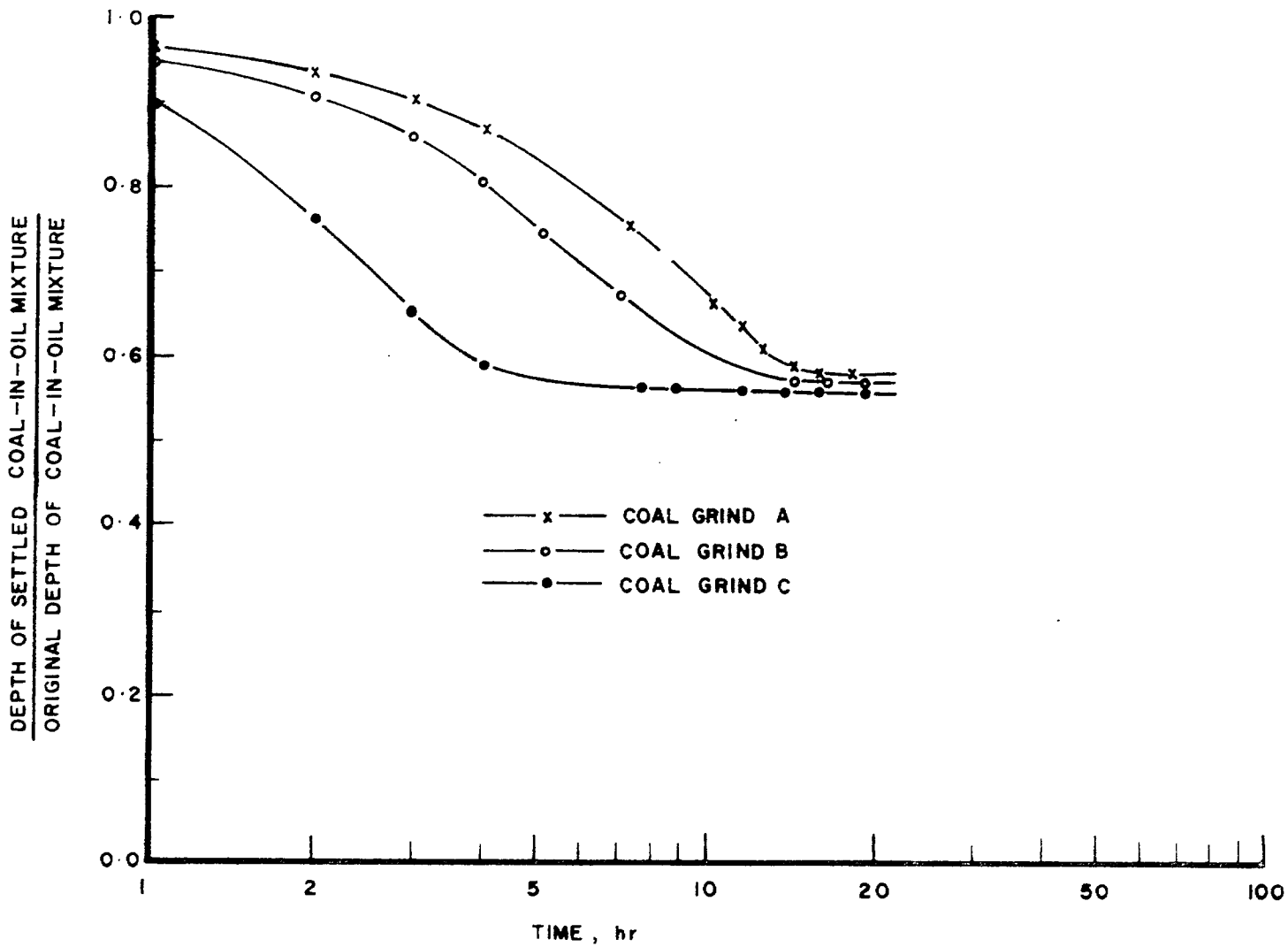


Figure 11. Stability characteristics of the coal in No. 2 oil.

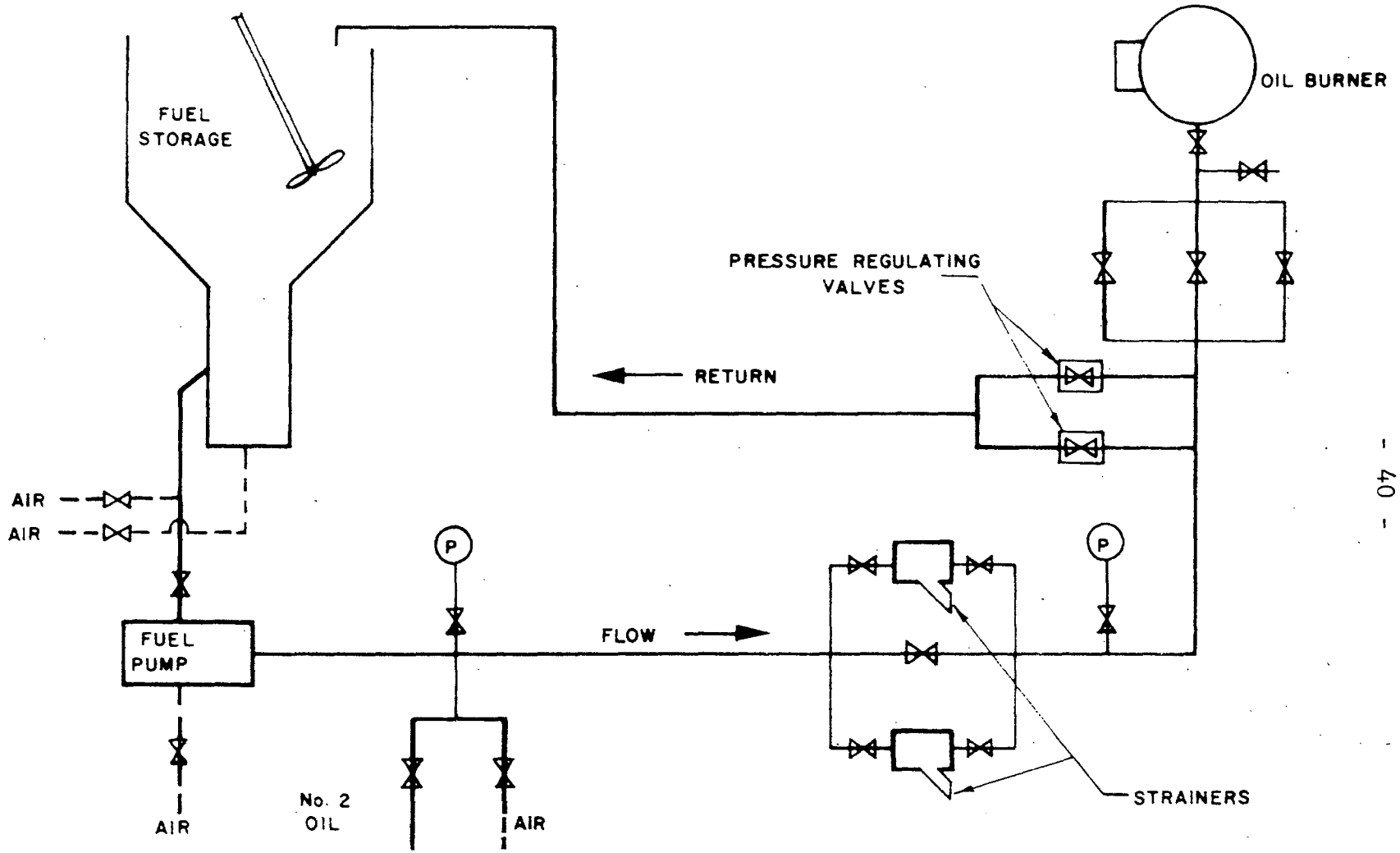


Figure 12. Schematic diagram of the coal-in-oil fuel storage and handling system.

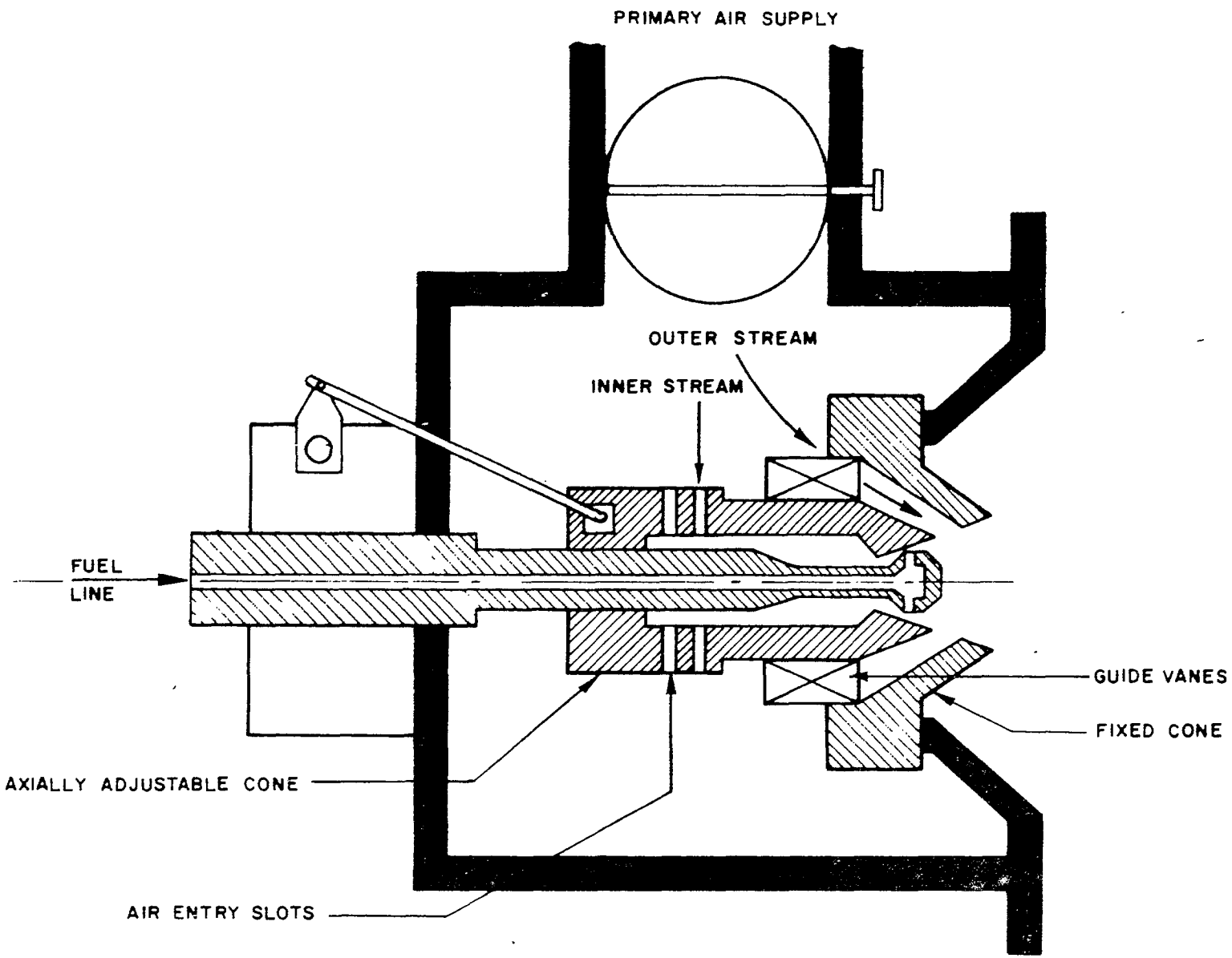


Figure 13. Schematic diagram of the coal-in-oil burner.

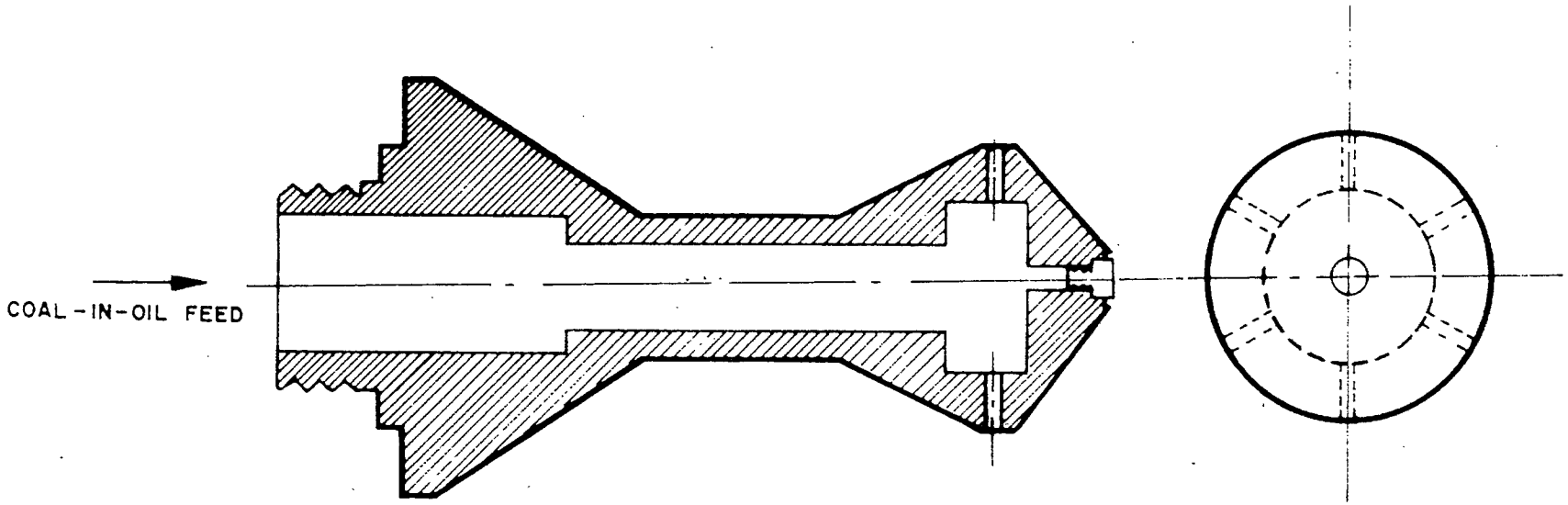


Figure 14. Schematic diagram of the coal-in-oil nozzle.