

ERL 89-35(0PJ)
c.1

CANMET

Canada Centre
for Mineral
and Energy
Technology

Centre canadien
de la technologie
des minéraux
et de l'énergie

**Energy
Research
Laboratories**

**Laboratoires
de recherche
sur l'énergie**

COMBUSTION AND HEAT CHARACTERISTICS
OF
BITUMEN EMULSIONS

H. Whaley and G.N. Banks
Division Report ERL 89-35(0PJ)

01-7986940 c.2



Canada



Energy, Mines and
Resources Canada

Énergie, Mines et
Ressources Canada

COMBUSTION AND HEAT CHARACTERISTICS
OF
BITUMEN EMULSIONS

H. Whaley and G.N. Banks
Division Report ERL 89-35(OPJ)

For presentation at the
International Flame Research Foundation (IFRF)
9th Members Conference, IJmuiden,
The Netherlands, May 24/26, 1989.

COMBUSTION AND HEAT TRANSFER CHARACTERISTICS OF BITUMEN EMULSIONS

by

H. WHALEY and G.N. BANKS, EMR CANADA/CANMET

ABSTRACT

A number of today's technologies produce a bitumen-water emulsion owing to either the recovery process, i.e. in situ extraction, or possibly pipe-lining bitumen to the refinery and using water as a viscosity reducing agent. Can these emulsions be used as a fuel directly and if so what are their combustion and heat transfer properties? A research program was undertaken to compare the combustion of bitumen and several emulsions with heavy fuel oil. It has been shown that the combustion performance of bitumen is not dissimilar to heavy fuel oil and that its performance can be improved when the moisture content is controlled between 10 and 20 wt %. There appeared to be little difference between air and steam as an atomizing medium. It is recommended that close attention be paid to atomizer selection if there is a possibility of the emulsion containing particulate material such as sand. This material can give rise to severe atomizer erosion if wear resistant materials are not utilized.

INTRODUCTION

The role of water in fuel oil combustion has a long history, dating back to the introduction of the steam-atomized burner and beyond. In the past half century, there have been periodic resurgences of interest in emulsified fuel oils. More recently, stricter environmental regulations, pipelining and handling applications as well as enhanced oil recovery methods have focussed attention on these products for combustion applications. Reduced environmental emissions from emulsified oil combustion compared to fuel oil are postulated to be due to so called "micro-explosions" (1) which occur as the water is rapidly heated when passing through the pre-combustion zone. This further disrupts the oil spray producing enhanced atomization, better combustion and thereby lower soot emissions. The resulting ash particles, which contain less soot, are able to pass through boiler tube banks with a much lower deposition rate than would occur with soot contaminated ash. Lower flame temperatures, due to the presence of water, should result in lower NO_x production in the flame.

Many technologies have been developed which produce stablized emulsions for combustion, pipelining or other forms of transportation and refining. Some of these are devices to produce mechanically-stablized fuel emulsions. Others are the result of enhanced oil recovery technology, in which steam is injected into the reservoirs, and the resulting bitumen emulsion is recovered for refining or may be used as a fuel for the in-situ recovery steam production. Significant developments have also been made in the production of bitumen emulsions for pipelining, refining and combustion applications, notably in Venezuela, Canada, the U.K. and the U.S. (2,3,4).

RESEARCH PROGRAM

A combustion and heat transfer evaluation of emulsified bitumen was undertaken by the Combustion and Carbonization Research Laboratory (CCRL) of the Canada Centre for Mineral and Energy Technology (CANMET). This project was undertaken in cooperation with the Alberta Oil Sands Technology and Research Authority (AOSTRA) and the Union Oil Company of Canada Limited. The project was undertaken to assess the feasibility of using recovered contaminated crude bitumen as a fuel for a small demonstration in-situ extraction plant, located at Cold Lake in northeastern Alberta, where a large reservoir of crude heavy bitumen exists.

The present paper describes the CCRL research facilities, the experimental project undertaken and gives an evaluation of the test results and updates material previously presented (5). The project was undertaken as part of the CANMET Mineral and Energy Technology Program, Energy Technology Activity and was supported in part by AOSTRA. All of the fuels tested were supplied by Union Oil.

OBJECTIVES

1. To demonstrate whether "as-recovered" bitumen contaminated with water, sand, carbonates and other impurities, can be used as an alternative fuel to natural gas to produce steam for the in-situ extraction process.
2. To determine whether it is necessary to reduce the water content or remove the contaminants in the "as-recovered" bitumen.
3. To compare the combustion and heat transfer characteristics of emulsified bitumen with No. 6 fuel oil.

4. To compare air and steam as atomizing media.
- 5 To assess the gaseous and particulate emissions produced during combustion.

FUEL PROPERTIES

Table 1 gives an analysis of the bitumen samples and the No. 6 fuel oil. The three bitumen samples contained 26%, 18% and nominally zero water content. On a dry basis the bitumen has a slightly lower heat content than the No. 6 fuel oil and contained 5.3% S and 4.3% ash. The bitumen ash composition is also given. The vanadium content is 223 ppm and the chlorides from the aqueous component are 375 ppm. Examination of the sediment in the bitumen showed that it contained 22% quartz, 62% dolomite, 12% kaolinite and 4% illite with traces of feldspar and anhydrite.

Examination of the emulsions showed that the water was dispersed in the bitumen in droplets of less than 50 mm (Fig. 1). Heating and freezing tests indicated that the emulsions could be easily reconstituted by simple mixing, provided the bitumen was warm (25°C) and also that water could be readily re-dispersed should it be necessary to offset evaporation losses.

5.0 EXPERIMENTAL EQUIPMENT AND PROCEDURES

5.1 CCRL Tunnel Furnace: The experimental program was carried out in the CCRL tunnel furnace illustrated in Fig. 2. This furnace has a maximum thermal input of 2.5 GJ/h (0.75 mw) and consists of 28 parallel-connected calorimeters which form a cylindrical chamber 1 metre in diameter and 4.25 metre long, plus a 1 metre long refractory-lined adiabatic combustion chamber. Each calorimeter is part of a coolant circuit and contains an

individual flow control valve, a variable area flowmeter and inlet and outlet thermocouples. An access slot along the length of the furnace wall permits the use of combustion probes to measure flame properties (6).

5.2 Tip Emulsion Burner: A commercial burner was modified by CCRL for the in-house coal-water fuel combustion and heat transfer characterization program. However, for this project, the atomizer was also modified and is shown schematically in Fig. 3. The secondary combustion air has a swirl number of about 0.5 from a 70° fixed-vane swirler located at the burner exit. The air atomizer typically operates at 69 to 207 kPa and is recommended for use with heavier fuel oils such as residual or Bunker C fuel oil. In the case of bitumen, the fuel temperature has to be maintained above 120°C, in order to attain effective atomization and flame stability.

5.3 Fuel Storage, Handling and Supply System: The fuel supply system is shown in Fig. 4. The tanks were located close to the furnace which reduced fuel-line heat loss and facilitated purging with light fuel oil at the conclusion of each test. The fuel supply system consisted of a 2000-L heated blending-tank and a 600-Litre heated day-tank. Each was mounted on electronic weigh scales. Each tank was heated and equipped with a return loop from a controlled pressure surge tank which would operate in the event of a line blockage. Each tank was agitated with a blade impeller to provide good fuel mixing. In addition, the day tank had a recycle loop that could be opened to purge the line to the burner with light fuel oil. Two high-voltage electrical heaters were used to preheat the fuel to about 125°C.

5.4 Experimental Procedure

The following parameters were held constant for the tests.

1. Thermal input - 1.7 GJ/h
2. Excess oxygen - 3 %
3. Combustion air temperature - ambient, except for steam atomized flame studies
4. Combustion air swirl level - about 0.5 from a fixed vane swirler
5. Burner fuel temperature - 125°C

The following parameters or operating conditions were varied in order to compare the particular flame:

1. Fuel pressure and temperature
2. Atomizing medium, flow and pressure
3. Emulsion moisture content

The project required that the combustion air not be preheated for the air atomized tests. However, when operating with steam atomization, preheated air of 155°C was used. This produced flame properties similar in shape and stability to the air atomized flames, while at the same time minimizing the atomizing steam.

The following parameters were measured for each test:

1. Total heat transfer to each furnace cooling circuit.
2. Incident radiative heat flux by ellipsoidal radiometer at the 0.5 and 3 metre locations.
3. Incident total heat flux by heat flux probe at the 0.5 and 3 metre locations.

4. Radial flame temperature profiles by suction pyrometer at the 1.0 and 2.2 metre locations.
5. Furnace exit gas temperature and composition including particulate emissions.

The tunnel furnace was preheated for about 3 h on light fuel oil, before switching to emulsified bitumen or No. 6 fuel oil. During this period the heated bitumen was recirculated. The operating parameters for the flame were then set and about 3 to 4 h were required before thermal equilibrium was attained. A similar period was required when conditions were changed. Thermal equilibrium was assessed by a series of thermocouples located along the inside of the furnace. At the end of each series of tests, the fuel lines were purged with light fuel oil, which was left in the line until the next series of tests.

6.0 DISCUSSION OF RESULTS

6.1 Atomizer Wear: A number of problems were anticipated with the combustion of sand-contaminated emulsified bitumen. CCRL has been extensively involved in the development of coal-liquid mixture (CLM) combustion technology (7,8). It was expected that the sand in the fuel would cause burner tip wear, leading to a deterioration in atomization. Examination of the burner tip before and after the combustion tests revealed some wear as shown in Fig. 5, but the test period was not long enough to cause the combustion performance to become unacceptable. However, it is suggested that on the basis of CLM experience, that a wear-resistant burner would be more suitable for long-term use with sand-contaminated bitumen (9).

6.2 Fuel Moisture Content: Much evidence in the literature suggests that optimum levels of moisture in fuel can be beneficial with respect to both combustion performance and the levels of emitted and deposited particulate material (10). However, there are some extravagant claims regarding improvements in boiler performance and some of these must be disputed. Doohar (11), Whaley (12,13) Livingstone (14) and Cook (15) have all shown that combustion and environmental benefits may only be marginal in some combustion equipment, while greater improvements are possible in others. It is reasonable to expect that modern combustion equipment will gain the least benefit from emulsified fuels, whereas older equipment, which is poorly maintained, will show the most improvement in combustion and heat transfer performance.

6.3 Flame Observations: Table 2 summarizes the furnace operating conditions. The No. 6 fuel oil produced a bright stable flame about 1 metre long and 0.5 metre in diameter. Generally, for the bitumen tests, the fuel temperature had to be kept above 120°C. Otherwise the flame would dip downwards and impinge on the floor of the furnace. The shape of the flame did not change significantly, being about 1 metre long and between 0.2- 0.5 metres in diameter. When operating with steam atomization a marked increase in sparklers (burning large droplets) was observed, especially if the atomizing steam pressure was allowed to rise above saturated steam conditions. In the case of air atomization, pressures above 172 kPa caused flame lift-off and unstable flame conditions. The following additional comments can be made:

- Emulsion temperatures in the day tank and fuel lines must be maintained above 85°C for satisfactory pumping to the burner and all fuel lines should have provision for flushing with light fuel oil.
- The emulsion supply system should have provisions for coarse filtering before the day tank and finer filtering before the pump to remove grit and sand. A pressure gauge to give advance warning of filter plugging is recommended.
- In-line heaters should be a low watt density electrical or a steam heat exchanger to prevent coking in the heating elements and subsequent deterioration in heating capacity.
- Stable flames with good combustion require a minimum fuel temperature of 120°C with enough pressure to prevent flashing of water to steam at the burner tip. It was found that a pressure corresponding to 10°C below the saturation temperature eliminated flame instability and sputtering.
- Flame stability can be improved by a refractory quarl or through the use of a continuous pilot flame.

6.4 Influence of Moisture Level on Heat Transfer and Flame Temperature:

Table 3 gives the furnace emission and heat transfer parameters. The flame temperature profiles across the furnace at the 1.0 and 2.2 metre locations are shown in Fig. 6. It can be seen that the higher moisture bitumen flame produced higher flame temperatures close to the burner than did No. 6 fuel oil.

Measured total heat flux and radiative heat flux are shown to decrease linearly with distance from the burner in Fig. 7. This observation is true for all the emulsion samples and No. 6 fuel oil. The radiative component appears to be between 70 and 75% of the total heat flux which is typical of No. 6 fuel oil combustion in pilot-scale equipment. Figure 8 shows the axial variation of heat absorption for all the tests.

Figure 9 shows the integrated total heat absorption for the furnace normalized with respect to the No. 6 fuel oil baseline and plotted against fuel moisture content. A similar plot is made of normalized furnace efficiency (ASME heat loss method PTC38) and both curves show similar trends as expected - since each is a measure of the ability of the furnace to extract heat from the flame. Previous work (11) had indicated that an optimum moisture content might be expected and it was observed that moisture levels between 10 and 20% provided marginally better furnace efficiencies than the lower moisture bitumen. However, this less than 10% gain can hardly be called significant. Clearly, a significant deterioration of heat-absorption performance at high and low moisture contents occurred when compared to the baseline fuel oil.

6.4 Influence of Moisture Level on Particulate and Gas Concentrations and Emission Rates: Figure 10 illustrates the CO_2 and O_2 profile measured across the flame at the 1 metre location. It can be seen that most of the profiles show the usual O_2 deflection on the flame axis. The most marked in this respect is the higher moisture-content bitumen flame. It is interesting to note that no variation exists for the steam atomized flame, indicating that the rapid fuel/air mixing which occurs in such flames is due to improved atomization. Table 3 and Figs. 11 and 12 illustrate the concentrations and emission rates of SO_2 and

NO variation with fuel moisture content. In addition, Fig. 12 shows that the particulate matter emission increases with fuel moisture content. This appears to contradict other findings in oil emulsion combustion (10,12) which showed either no change or a reduction in particulate emissions with increased moisture content. As expected SO₂ emissions decreased linearly with fuel moisture content.

The NO variation is slight and as expected, the highest level occurs in the range of peak heat transfer absorption between 0 and 20 wt % moisture. For comparison the SO₂ emission rate of about 2 kg/GJ is well in excess of the Canadian federal guideline of 0.258 kg/GJ and would require SO₂ removal equipment. However, in Alberta, each plant is granted an operating permit on an individual basis and the remote location and unavailability of alternative fuels would probably be considered. NO emissions of about 0.1 kg/GJ are comparable with the federal guideline of 0.084 kg/GJ for new oil-fired boiler plants (16). These could easily be further reduced by use of staged combustion equipment. The emission rates of particulate matter are high compared with No. 6 fuel oil and would exceed the federal guideline of 0.043 kg/GJ for new oil-fired boiler plants if particulate collection equipment were not utilized.

7.0 CONCLUSIONS

Tests conducted in the CCRL pilot-scale tunnel furnace on emulsified heavy bitumen, containing up to 26% wt% moisture, indicate:

1. Emulsified bitumen is an excellent boiler fuel that can be used on-site as a substitute for fuels that would have to be brought in to the proposed remote northerly location.

2. The fuel can be handled satisfactorily, providing the temperature in the day-tanks and fuel-lines is kept above 85°C to give satisfactory pumping performance. Few problems are encountered if the temperature of the fuel supply to the burner is kept above 120°C.
3. A twin-fluid tip atomizing burner was utilized with minimal wear during the 20 h of testing with bitumen. It is recommended that close attention be paid to burner selection in order to minimize the wear which would probably occur with the prolonged use of contaminated emulsified bitumen fuel.
4. The combustion and heat transfer performance is similar to that of No. 6 fuel oil in the range of moisture contents from 10 to 20 wt%. Outside that range the comparable performance deteriorates. There appeared to be very little difference between air and steam atomization of the zero moisture bitumen when the heat transfer performance was compared.
5. Emission rates of SO₂ and particulates are significantly above the guidelines recommended by Environment Canada but NO emission rates are comparable with those recommended in the guidelines. In practice the latter can be still further reduced by use of staged combustion equipment.

8. REFERENCES

- (1) V.M. Ivanov, B.V. Kantrovich, L.S. Rapiovets and L.L. Khotuntsev, Fuel emulsions for combustion and gasification, J. Acad Sci. U.S.S.R., 5 p. 56; (1957).
- (2) F. Pass and F. Schwarz, Combustion of liquid fuels: very heavy fuel oils; V.G.B. Kraftswerktechnik 57, 11 p. 723; (1977).
- (3) K.R. Olen, J.P. Doohar and L.M. Woodsworth, Emulsified heavy ends: a new family of slurry fuels, Proceedings Fifth International Workshop on Coal-liquid Fuels Technology, Halifax, Canada, October (1985).
- (4) K.R. Olen, L.M. Woodsworth and J.W. Allen, Large-scale combustion experience with emulsified petroleum fuel, Proceedings Sixth International Workshop on Coal-Liquid and Alternate Fuels Technology, Halifax, Canada, October (1986).
- (5) G.K. Lee, H. Whaley and R. Prokopuk, The utilization of crude bitumen as a boiler fuel, Proceedings Engineering Foundation Conference on Combustion of Tomorrow's Fuels II, p. 473, Davos, Switzerland (1984).
- (6) F.D. Friedrich, E.R. Mitchell, G.K. Lee and H. Whaley, The CCRL tunnel furnace: design and application, Second Members Conference; IFRF, IJmuiden, the Netherlands (1971).
- (7) H. Whaley and P.J. Whalen, Burner nozzle wear during coal-oil mixture combustion trials in a small utility boiler, Paper No. 94, Corrosion 81 Conference; National Association of Corrosion Engineers, Toronto, Canada (1981).

- (8) L. Bruno, A.S. Deshpande and H. Whaley, Coal-oil slurry combustion and tribology: A Canadian experience, Proceedings Fourth International Symposium on Coal Slurry Combustion, Orlando Fl. USA (1982).
- (9) K.V. Thambimuthu and H. Whaley, Progress in the development of CWF burners for boiler and process combustor applications, Proceedings American Flame Research Committee Spring Technical Meeting, Toronto, Canada (1988).
- (10) R.E. Hall, The effect of water/residual oil emulsions on air pollutant emissions and efficiency of commercial boilers; ASME Journal of Engineering for Power; 10 p. 425; (1976).
- (11) J. Doohar, R. Grenberg, S. Moon, B. Gilmartin, S. Jakatt, J. Skura and D. Wright, Combustion studies of water/oil emulsion on a commercial boiler using No. 2 oil and low and high sulphur No. 6 fuel, Fuel 59, p. 883; (1980).
- (12) H. Whaley and D.G. Savignac, An evaluation of water in fuel oil emulsions in a small package boiler, Energy Research Laboratories, CANMET Report ERL 79-67(TR) (1979).
- (13) H. Whaley and G.K. Lee, Efficiency trials on Unit No. 3 Central Experimental Farm Heating Plant, Ottawa: A comparative evaluation of untreated and water emulsified No. 6 fuel oil, Energy Research Laboratories, CANMET Report ERL 79-19 (CF) (1980).
- (14) P. Livingston and A. Kuntz, Combustion of water/oil emulsions, Pulp and Paper Canada 80, 12 p. 147; (1979).
- (15) T.D. Cook, Water-in-oil emulsion firing in an industrial steam boiler, General Motors Report 415; (1977).
- (16) Canada Gazette - Thermal power generation emissions - national guidelines for new stationary sources, (1981).

Fuel	No. 6 fuel oil	Bitumen
Specific Gravity, (15.6/15.6°C)	0.993	1.060
Calorific Value, MJ/kg	42.9	40.1
Flash Point, °C	107	-
Kinematic Viscosity, cSt at 50°C	650	-
at 99°C	47	-
C wt%	87.61	81.70
H wt%	10.45	9.78
S wt:	1.54	5.25
N wt:	0.36	0.40
O wt:	<0.10	<0.10
Ash wt%	<0.10	4.27

Major Ash Elements in Bitumen, % dry fuel basis, by NAA

Al	0.21	K	0.02
CA	1.08	Na	0.06
Fe	<0.08	Ti	<0.02
Mg	0.63	Si	0.45

Minor Elements, ppm dry fuel basis, by AAS

Sb	0.2	La	1.2
As	<2.0	Lu	<0.2
Ba	<15.0	Mn	7.5
Br	1.0	Mo	<8.0
Ce	<45	Ne	<75
Cs	<3.0	Ru	<150
Cr	<8.0	Sm	0.04
Co	<2.0	Sc	0.2
Cu	<150	Sr	<75
Dy	<0.2	Ta	<8
Eu	<0.2	Th	<0.8
Hf	<0.8	U	<0.8
Ho	<2.0	Zn	<1.2
I	<15		
Ni	81		
V	223		

Chlorides 375 (aqueous component)

Table 1. Fuel Oil and Bitumen Analyses

Parameters	Test (Baseline)	1	2	3	4	5
Fuel	No. 6 oil			Bitumen		
Tank outlet temp, °C	68	92	93	98	106	
Burner temp, °C	125	124	124	124	123	
Pressure, kPa	441	655	392	448	427	
Moisture in fuel, wt % *	<0.1	26.1	18.0	0.2	0.2	
Thermal input, GJ/h	1.67	1.67	1.65	1.67	1.70	
Fuel input, kg/h (wet)	39.0	56.5	50.3	41.7	42.6	
Input water-oil ratio	<0.001	0.36	0.22	0.002	0.19	
Atomizing Medium	Air	Air	Air	Air	Steam	
Temperature, °C	32	36	35	33	155	
Pressure, kPa	241	241	255	248	571	
Flowrate, kg/h	10.5	8.2	10.5	20.9	8.2	
Secondary Air						
Temperature, °C	26	26	26	26	158	
Flowrate, kg/h	584	611	591	625	598	
Exit furnace temp., °C	620	620	630	650	615	
Exit furnace press., kPa	0.005	0.005	0.007	0.005	0.005	

* Xylene distillation, ASTM D95-70

Table 2. Furnace operating conditions

Parameters	Test (Baseline)	1	2	3	4	5
Flue Gas Conditions						
O ₂ , vol %		2.9	2.8	2.7	2.9	2.7
CO ₂ , vol %		13.7	13.9	13.8	13.7	13.7
CO, vol ppm		<100	200	170	180	160
NO, vol ppm		280	270	310	240	310
SO ₃ , vol ppm		1.0	2.0	3.0	13.0	6.0
SO ₂ , vol ppm		775	2400	2450	2500	2500
H ₂ S, vol ppm		100-125	<100	<100	<100	<100
		<100	<100	<100	<100	<100
Soot in particulate wt, %						
		<0.1	<0.1	0.8	8	7
Particulate loading, g/Nm ³		0.18	1.28	1.19	0.48	0.62
Particulate emission, Kg/GJ		0.05	0.38	0.35	0.14	0.18
NO emission, kg/GJ		0.10	0.10	0.12	0.09	0.12
SO ₂ emission, kg/GJ		0.60	0.89	1.93	1.98	1.98
Moisture loss, %*		0.08	2.17	1.51	0.02	1.26
Combustion efficiency, %		>99.0	>99.9	>99.9	>99.7	>99.7
Normalized furnace efficiency**		1.00	0.97	1.00	0.98	0.99
Normalized heat absorption		1.00	0.97	1.01	0.94	0.92
Flame length, metre		1-1.5	1.5 - 2	1.5	1-1.5	1.0
Flame diameter, metre		0.3-0.5	0.3 -0.5	0.2-0.3	0.2-0.3	0.2

* ASME PTC 38

** reference No. 6 oil = 1.00

Table 3. Furnace emission and heat transfer parameters

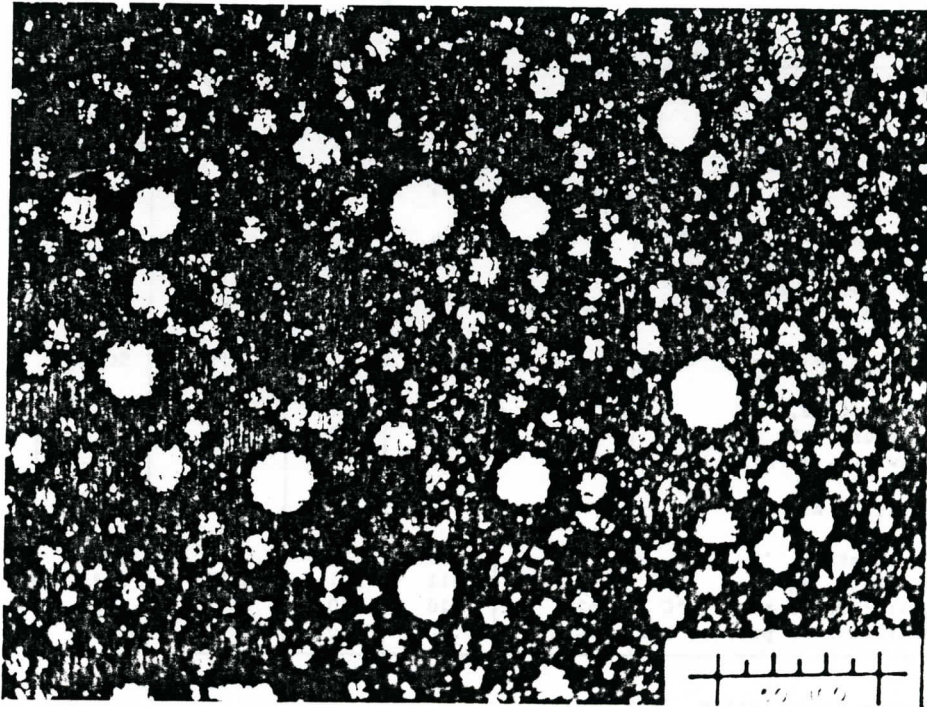


Figure 1 - Micrograph of emulsion containing 26% moisture, scale in micrometres

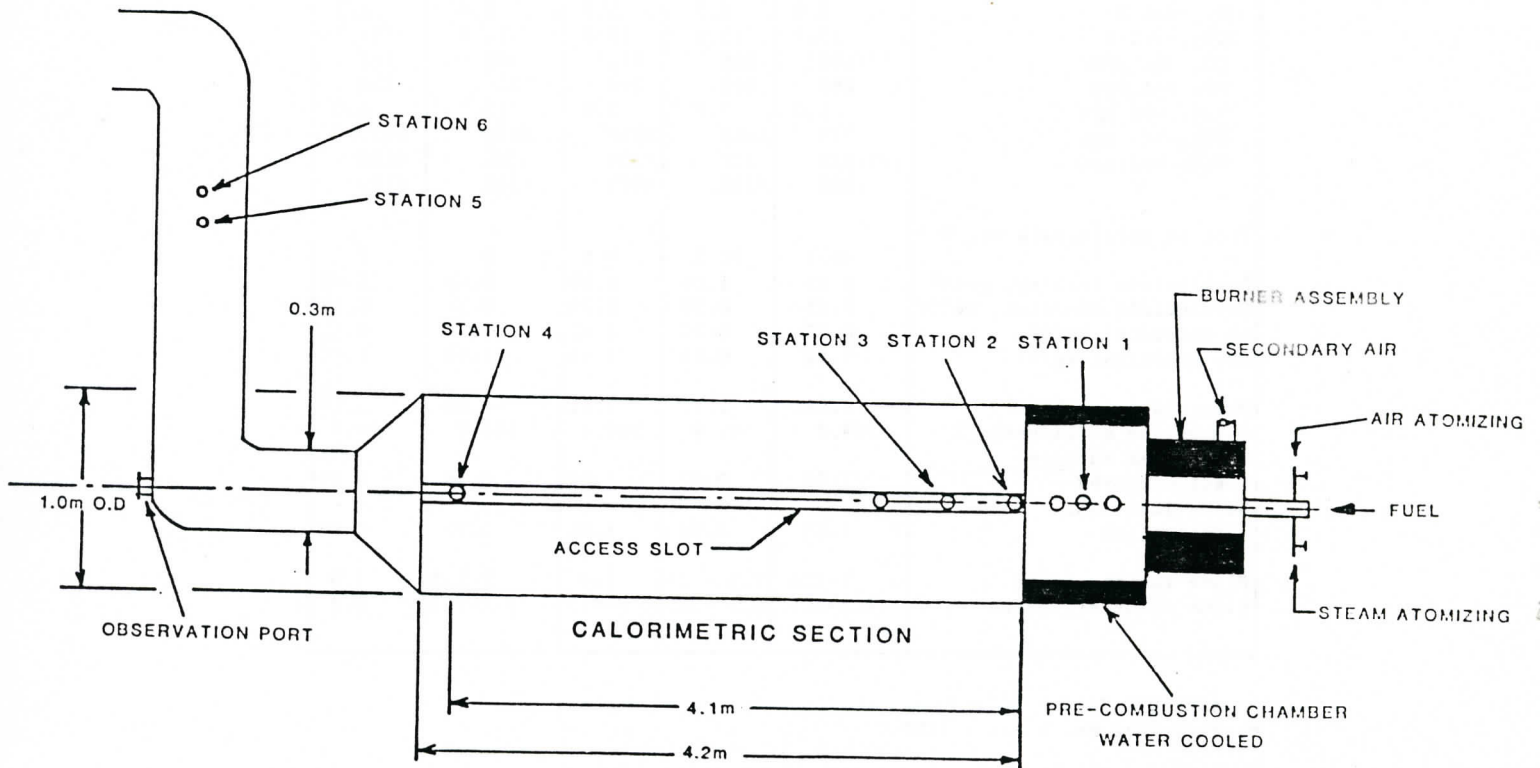


Figure 2 - Schematic illustration of CCRL tunnel furnace

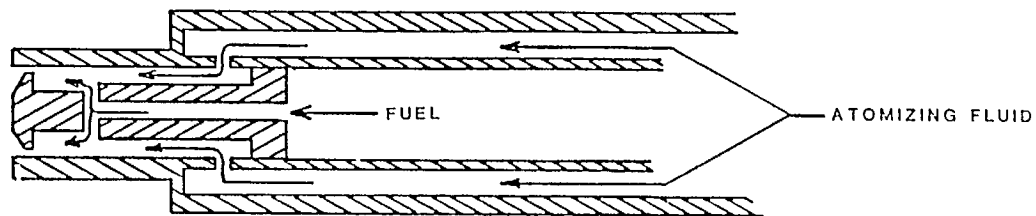


Figure 3 - Schematic illustration of atomizer

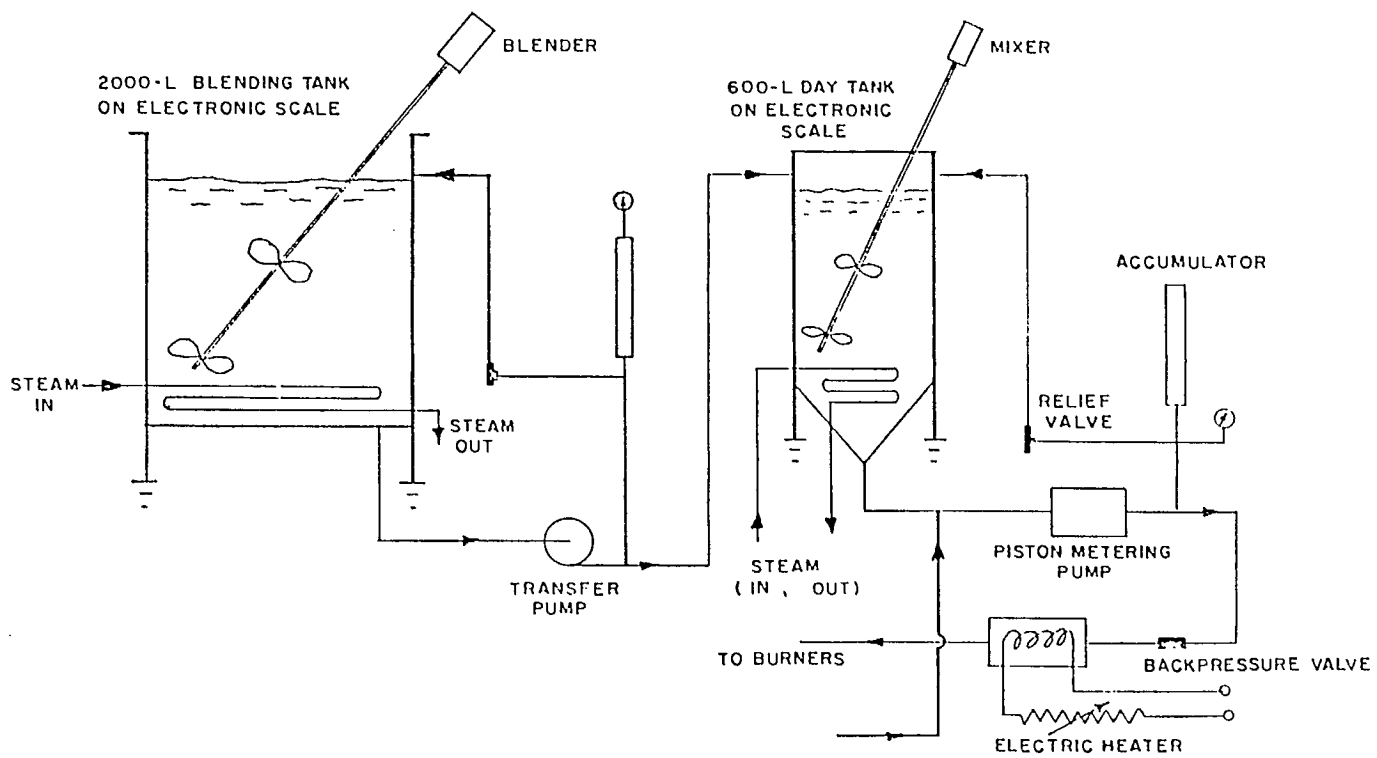


Figure 4 - Schematic illustration of fuel handling system

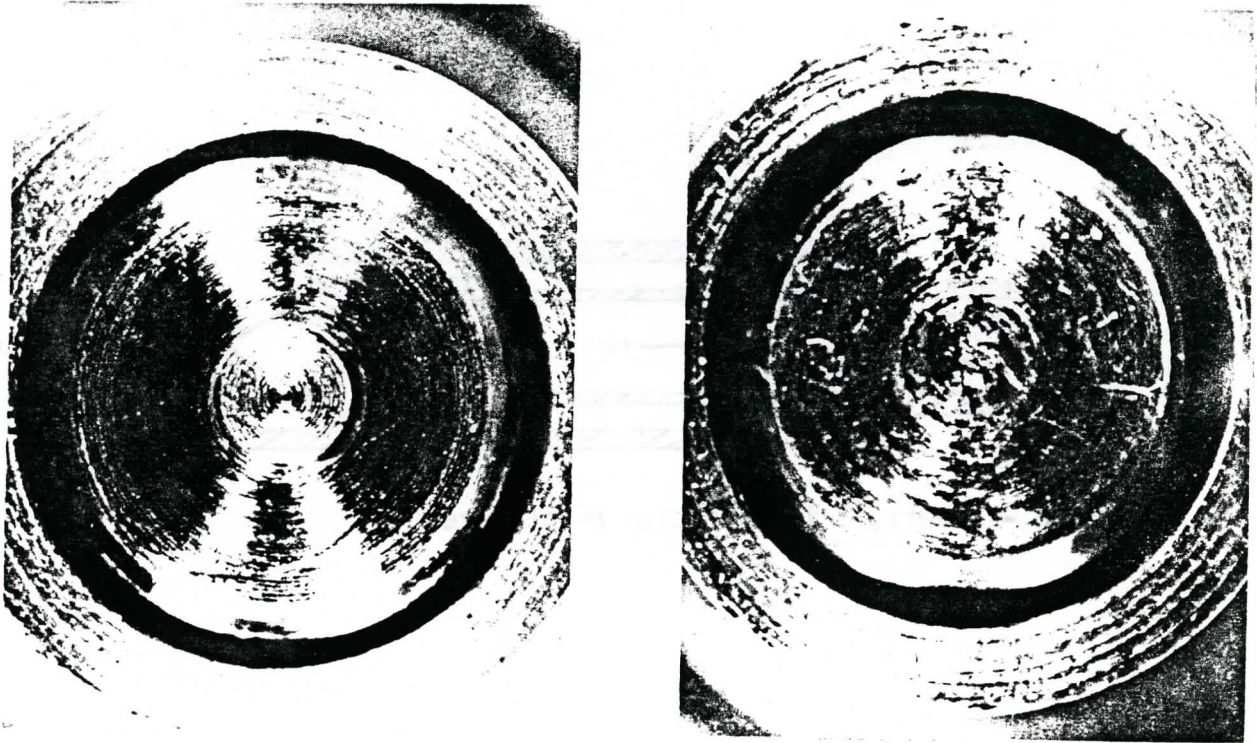


Figure 5 - Photograph of atomizer before and after 20h of combustion tests

- No 6 Oil
- ○ ○ ○ ○ Bitumen, 0% Moisture, Air Atomized
- · — · — Bitumen, 18% Moisture, Air Atomized
- × × × × × Bitumen, 26% Moisture, Air Atomized
- - - - - Bitumen, 0% Moisture, Steam Atomized

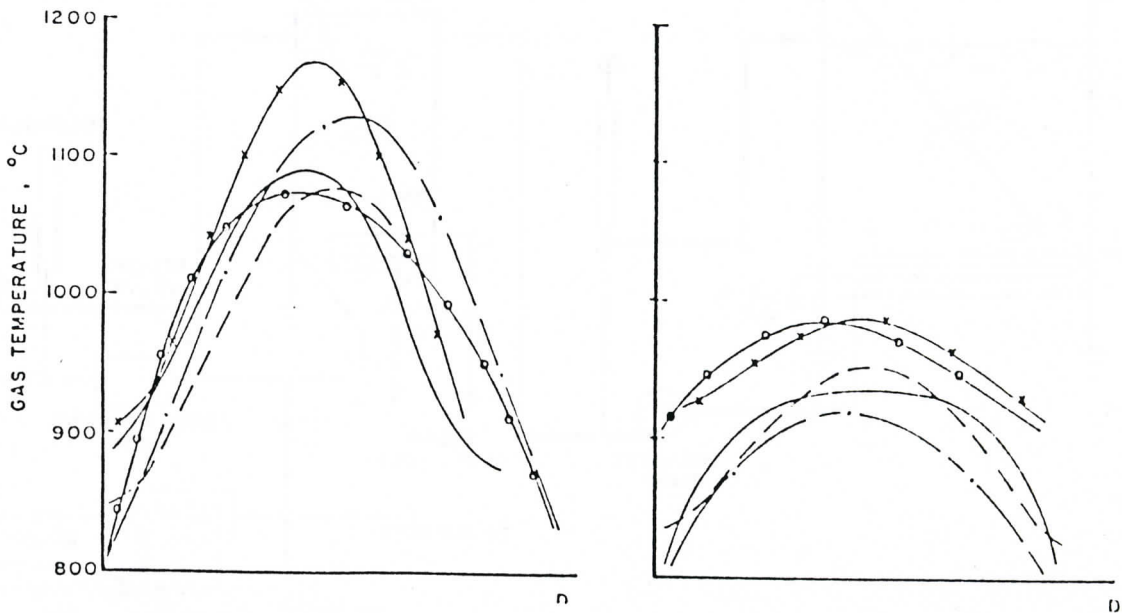


Figure 6 - Radial gas temperature profiles at the 1 and 2.2 in axial locations

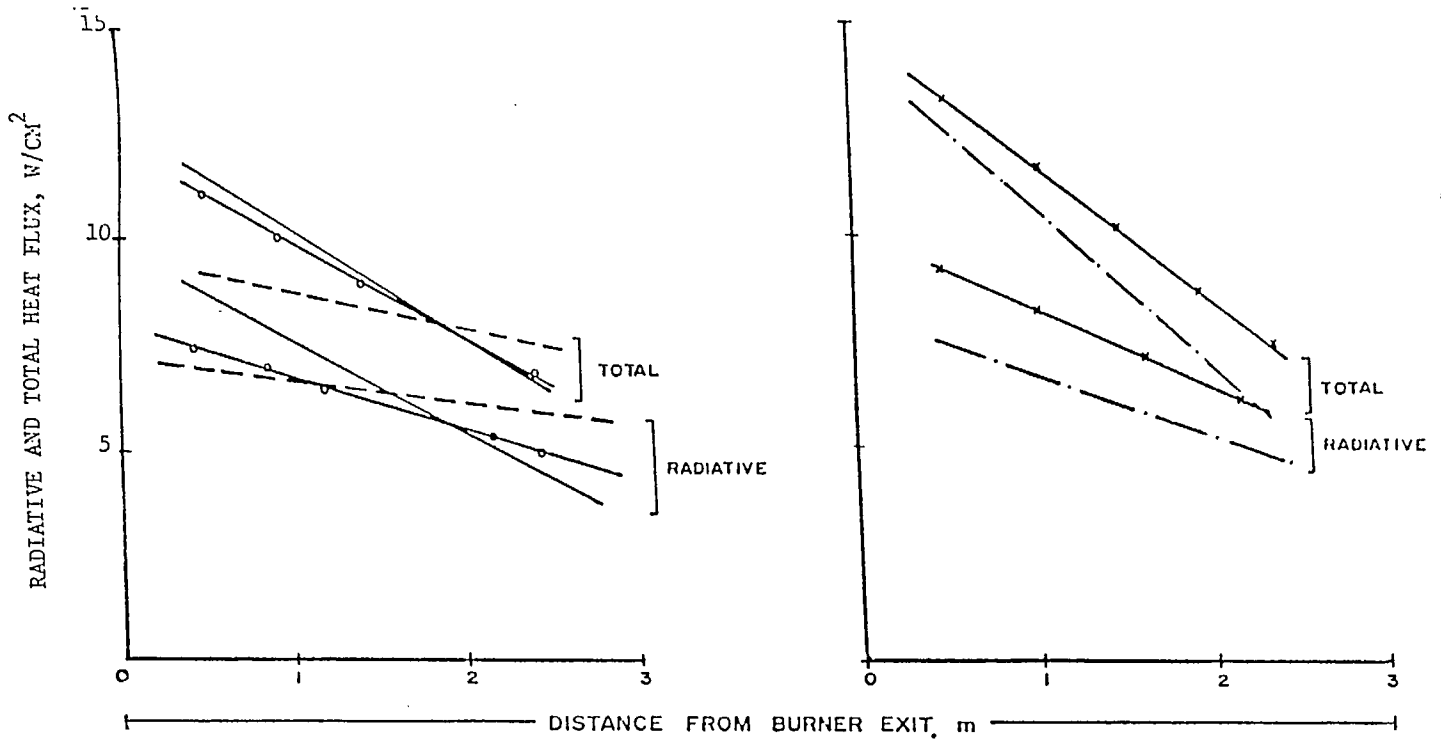


Figure 7 - Variation of axial radiative and total heat fluxes

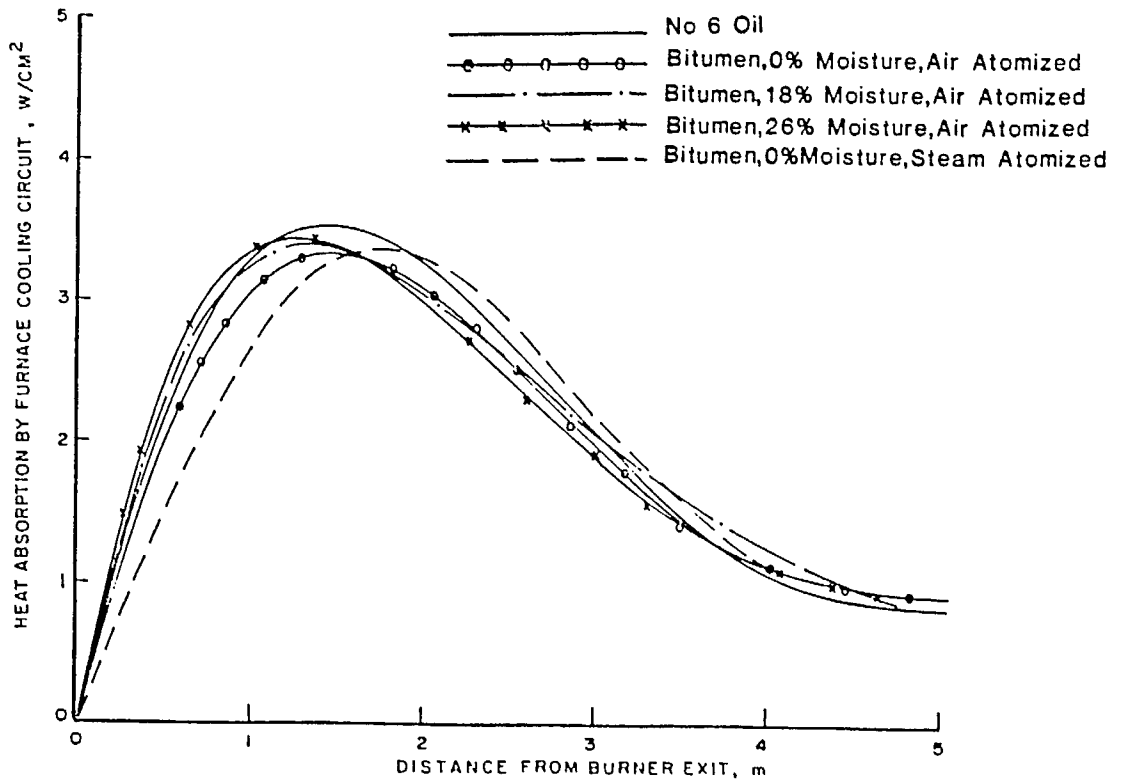


Figure 8 - Variation of axial heat transfer to cooling circuits

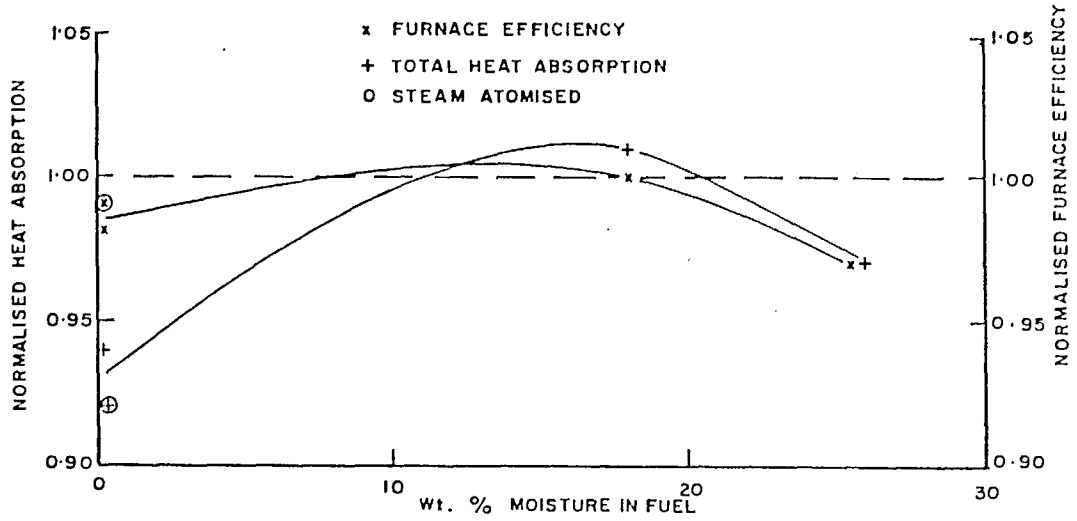


Figure 9 - Variation of furnace efficiency and heat absorption with moisture content

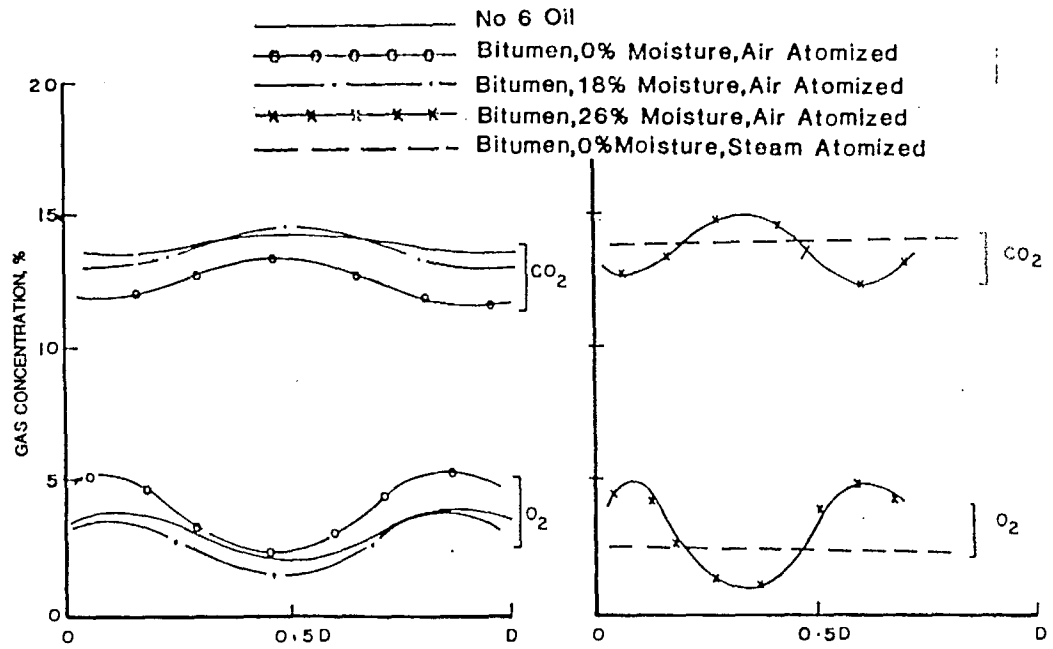


Figure 10 - Radial profile of O₂ and CO₂ at the 1 and 2.2 m axial locations

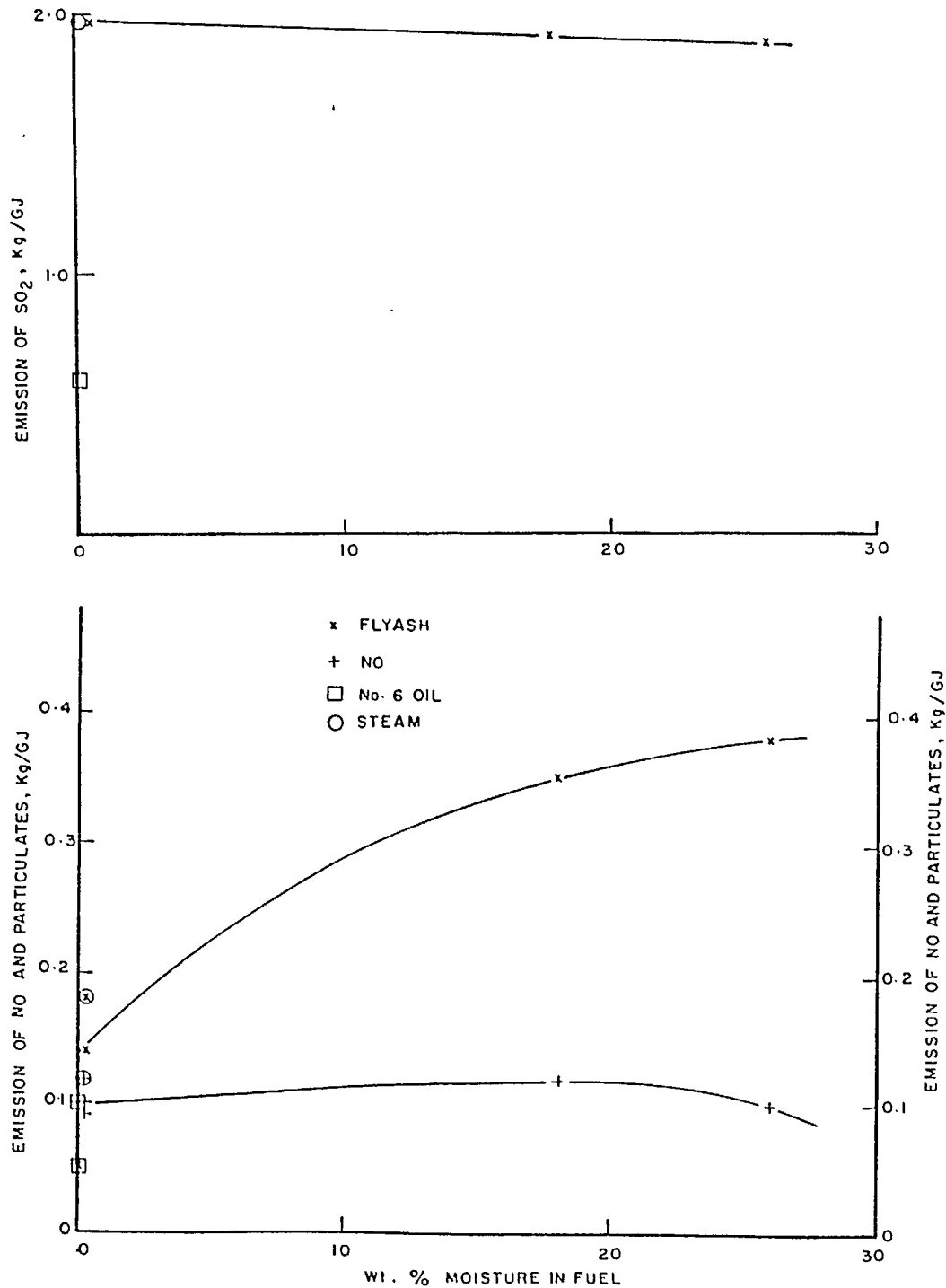


Figure 11 - Variation of SO₂, NO and particulate emissions with moisture content