

COMBUSTIBILITY AND INCINERATION OF BEAUFORT CRUDE/SEAWATER EMULSIONS

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ABSTRACT: Tests on the emulsification properties of two different Beaufort crudes have shown that emulsions with up to 50 percent water content have to be expected after an oil spill. Emulsions with this water content were burned in a very simple combustor, and the resulting flames were as clean as can be expected from any fuel. Since no problems were encountered while burning these emulsions, it seems that a low pollution incineration device can be designed using well-established standard design criteria.

A few years ago the authors were contacted by Dome Petroleum concerning the possibility of a contract investigating the incineration of oil recovered from the Beaufort Sea. The questions at issue were whether emulsions are formed in the Beaufort Sea, how they would behave, and how they might be incinerated. A severe constraint on any such study was the lack of accessibility of the area. All equipment had to be small enough to be transported by helicopter. The project with Dome never materialized, but because of the national interest in combating all forms of pollution a research program was pursued using Canadian NSERC grant funds.

Most incineration equipment (at least at that time) had to separate the oil from the water to burn the oil efficiently. Also, most devices (e.g., flare burners), while useful for burning large quantities, were too large for helicopter transportation.^{15,18} Typically, incineration of crudes is not very efficient, the flame being sooty and highly radiative. A major hazard is posed for the permafrost environment, locally, by the high flame radiation and, over a wide area, by soot deposition. One of the standard techniques for improving combustion of residual fuels is to add water and burn the emulsion formed. It seemed logical therefore to try to burn any emulsions formed with the Beaufort crude, eliminating at once the need for bulky emulsions breaking equipment as well as a major environmental problem.

Properties of Beaufort crude and its emulsions

Beaufort crudes are rather peculiar.² They are generally highly naphthenic, resulting in very low viscosities in spite of the relatively high density of the crude. A comprehensive literature survey through the databanks available to the Laval University library showed that no information was available on the emulsification characteristics of Beaufort Sea oil, nor on the properties of the emulsions it forms.

Two different crudes from the Beaufort area were studied in the present project: a Copanor N13, aged for several months in an open barge, and a fairly fresh Copanor 2I44. Their relevant physical properties are listed in Table 1.

Water-in-oil emulsions were easily formed from both crudes by shaking oil and seawater in the appropriate proportions for various durations at both 0° C and room temperature. No significant differences were found in the emulsification characteristics at the two temperatures. The highest water content possible was 70 percent (all

percentages in this paper are given as percent of the total emulsion by volume). At 70 percent water, no further progress in emulsification was found after one hour of shaking. Emulsions with 10 percent water had to be shaken for two hours before no further progress was found. Microscopic observation showed all emulsions to be of the water-in-oil type. Oil-in-water emulsions could not be formed.

With decreasing water content the emulsions became more homogeneous and the mean diameter of the water droplets became smaller. For all emulsions, minimum drop size was below 10 μm . For the 50 percent emulsion, drops ranged up to 50 μm in diameter; with 30 percent water very few droplets above 30 μm were found; and with 10 percent water only a few droplets above 10 μm were found.

The stability of the emulsions proved to be quite variable. All emulsions separated eventually; only a very thin layer of emulsion with a very low water content did remain at the interface. This interfacial layer was extremely stable under quiescent conditions, but it was rapidly destroyed by slight agitation. All emulsions with more than 50 percent water started to separate immediately after stopping the shaker. At room temperature all emulsions with 50 percent or less water were relatively stable. The less the water content, the longer it took for water to come out of the emulsion.

At low temperature the emulsions formed with the aged N13 showed the same general behavior, with some minor loss of stability, whereas the emulsions of the 2I44 completely lost stability at more than 20 percent water.

Viscosities of the emulsions were measured at 0° to 2° C and at room temperature. No clear deviation from newtonian behavior was found. However, a fair amount of scatter of the measured values indicated the probability of some deviation. Viscosities of the emulsions from the N13 were measured at 0° and 26.5° C using Ubbelohde viscometers and at 2° and 23° C using a Brookfield viscometer with two different rotors having five different speeds each. Emulsions of the 2I44 were measured at 26.5° C in the Ubbelohde tubes. Table 2 and Figures 1 and 2 show the viscosities measured.

Table 1. Properties of fuels

Property	Fuel	
	N13	2I44
Density (kg/m ³)		
15° C	902.5	—
23° C	889.0	882.5
Original water content (percent volume)	6.4	2.2
Surface tension (N/m)		
Crude-air	29.35×10^{-3}	27.8×10^{-3}
Crude-water	13.65×10^{-3}	21.6×10^{-3}

Note: Seawater density = 1006.5 kg/m³, surface tension of water-air = 69.45×10^{-3} N/m

Table 2. Emulsion viscosities

Kinematic viscosity, cs (10 ⁻⁶ m ² /s)				Dynamic viscosity, cp (10 ⁻³ Pa.s)				
Percent water content	N13		2I44	Percent water content	N13		2I44	
	0° C	26.5° C	26.5° C		2° C	23° C	2° C	23° C
0	81	21.4	11.6	0	53	32	61	14.2
10	94	25.4	15.0	10	69	39	76	17.3
20	138	34.2	20.1	20	101	51	100	22
30	201	51.5	57.8	30	147	66	192	32
40	324	80	82	40	228	89	343	53
50	497	118	93	50	404	156	484	96
60	863	207	—	60	915	349	613	220
70	1,750	353	—	70	3,200	525	—	—

Note: Water content not corrected for original water content of the crudes

Combustion properties of emulsions

The beneficial effects of water-in-fuel emulsions on the combustion process were probably first noticed during World War II, when water injection was used in high performance piston engines to improve the knock rating of the gasolines and the overall engine performance. At the time, it was noticed that adding the water in the form of an emulsion was much more efficient than independent water injection. Engine performance was improved well beyond what was expected.⁶

After the war, the concept of burning water-oil emulsions was advanced by Ivanov *et al.*⁹ They reported experiments where high speed photography of single emulsion droplets introduced into a hot chamber showed that these droplets went through a faster and more disruptive combustion process than pure fuel droplets. They proposed the explanation that the rapid evaporation of the water in the droplets ruptured the droplets (in microexplosions). They concluded that water in emulsified fuels did not impair but improved combustion due to the breaking of the droplets, which increased the evaporation surface and improved the mixing of fuel with air. The ensuing reduction of combustion time had a favorable influence on the burnout of sooty residue.

Since then, burning of emulsions has become a generally accepted method of improving heavy fuel combustion. Most experience with emulsified fuels showed significant reductions in soot and NO_x emissions. Barrett *et al.* report a substantial reduction in smoke levels and a reduction in NO_x from around 400 ppm to about 100 ppm when using 20 percent water in No. 6 fuel oil.¹ (Many references do not specify whether percentages given are percentages of the emulsion or of the fuel.) Goldstein and Siegmund used up to 30 percent of residual fuel oil in emulsions and found that moderate amounts of water

emulsified in fuel oil can reduce particulate emissions, primarily large and intermediate-sized particles. They explain this mainly by a delay of cracking due to the presence of water.⁸

A reduction in soot emissions was also observed by Cunningham and Jackson.³ Melion *et al.* report not only a reduction in particulate emissions by 90 percent (mass), but also a decrease in size, a very substantial reduction in NO_x levels, and a substantial reduction in the transformation of SO₂ into SO₃.¹² The improvement of the combustion process is again explained by microexplosions.

Dryer mentions the possible importance of kinetic effects of water,⁵ which, especially in the rich parts of diffusion flame structures, lead to enhanced oxidation of soot precursors. The existence of this mechanism seems assured, since a reduction of soot emissions can be found even in premixed fuel-air-steam flames.¹⁴ Various beneficial effects of emulsified fuels have been described,^{7, 10, 13, 16, 17, 19} and a fairly comprehensive review is given by Dryer.⁴

It may be presumed that the use of emulsions is beneficial to combustion, then, in reducing NO_x (probably just due to the lowering of maximum flame temperatures), and in reducing soot emissions (through three possible mechanisms—kinetic effects, lowering of flame temperatures, and microexplosions).

There is some indication that microexplosions occur only with residual fuels or at elevated pressures. The limit on the amount of water in the emulsion depends on the type of fuel and burning conditions. With a light fuel and lean mixtures, an optimum seems to be reached at 5 percent water;¹¹ this limit increases with increasing residual content of the fuel and increasing richness of the mixture. A limit is reached in all cases at about 50 percent (mass) of water in the emulsion. Increasing the water content beyond leads to excessive quenching effects and a drastic increase in CO and unburned hydrocarbons and eventually to flame extinction.

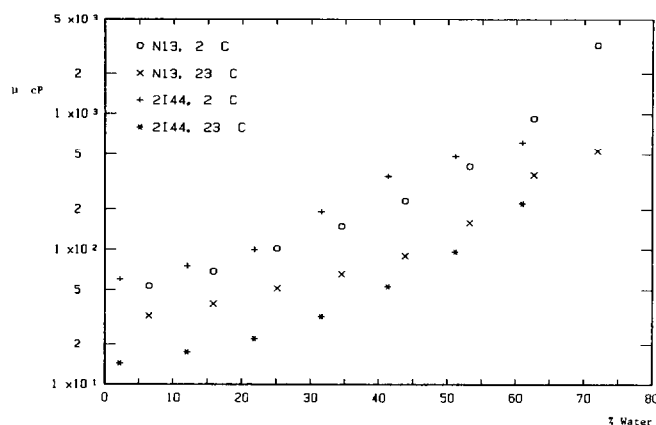


Figure 1. Dynamic viscosity

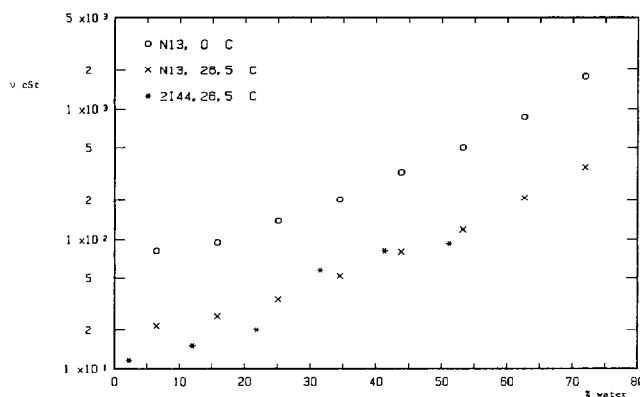


Figure 2. Kinematic viscosity

Combustion testing of Beaufort oil emulsions

For the present work it was decided to modify an off-the-shelf burner used in domestic heating applications. This burner had to be modified in two ways. The pump used for pumping domestic fuel to about 700 kPa was obviously not sufficient for the purpose. Also, these burners are not designed for burning in the open, so a combustion chamber had to be designed and fitted onto the barrel of the burner.

Atomization tests were performed by spraying (without combustion) into a ventilated plexiglas box of about 2 m³ volume. Visual and photographic evaluation indicated that adequate atomization was achieved for all emulsions (close to 0° C) with gauge pressures of about 1.3 to 1.5 MPa. Ratings of nozzles tested ranged from 0.75 to 1.5 U.S. gallons per hour at 100 psig. The nozzle used for the subsequent combustion tests had the 0.75 rating. The pump chosen eventually was a standard gear pump for hydraulic applications.

Before proceeding to the design of a combustion chamber, burning tests were performed using various types of flame holder configurations. All tests leading to the present configuration were performed outdoors at temperatures between 5° and about -15° C. Systematic tests varying flameholder type and distance from the burner eventually led to the present combustion chamber design, which is a cylindrical chamber 250 mm long and of 150 mm internal diameter. The chamber is lined with 25 mm of castable ceramic cement (outer diameter 200 mm). The end is closed by a ring baffle with an opening of 90 mm.

Combustion tests using this combustion chamber showed that emulsions containing up to 60 percent water could be burned successfully after preheating the ceramic lining, either using diesel fuel or emulsions with low water content. Emulsions with higher water content burned quite well initially. The low heat release, however, was insufficient to keep the ceramic lining hot and the flame rapidly deteriorated and eventually extinguished.

Even though the air-fuel mixtures were fuel-rich (with equivalence ratios of about 1.1 to 1.8) all emulsions flames were without visible smoke, in contrast to the diesel flame. Even the crude itself did not show signs of smoke, probably due to its initial water content. All flames were fairly luminous. Spectroscopic observation showed, however, that this luminosity was not due to carbon but to sodium from the seawater used.

With the original setup it was not possible to use lean mixtures due to insufficient airflow from the integral blower. Burning the crude at slightly lean mixtures showed the flame to be contained completely inside the chamber, with flame radiation too low to be measured.

Emulsions with 30 percent or less water could be ignited directly (using the standard incorporated igniter) with fuel pressures over 3 MPa. The pressure needed increased with increasing water content, the increase necessary for cold ignition being more than that needed to keep a constant SMD and, for more than 40 percent water the pressure needed exceeded the pump capacity (1,000 psig). Very satis-

factory ignition was achieved for all emulsions by preheating the combustor (usually with diesel fuel) and then switching over to the emulsion.

To perform quantitative measurements, the flame had to be contained, and therefore fuel-lean mixtures were necessary. Also, because of access problems, the test rig had to be moved into the combustion laboratories, where testing had to be done at room temperatures. For the quantitative tests air was supplied from an external blower and metered through an orifice plate. Flame containment was achieved by fitting a standard stovepipe over the end of the combustion chamber. To use single point sampling, a mixing plate was introduced into the pipe downstream of the combustor, and a conical sampler with a diameter of about 50 mm was placed facing upstream at a distance of about 2 m from the exit of the combustion chamber.

The flow rate of the emulsions from both crudes was increased with increasing water content so that the mass flow of oil was kept constant, taking into account the original water content. This procedure represents quite a range of total flows. Pump limitations allowed only one series of fuel flows. Airflow was kept constant for all emulsions with two different airflow rates in two series of tests. Emulsions tested ranged from crude to emulsions containing 50 percent water by volume. Measurements taken were CO₂, CO, unburned hydrocarbons, oxygen, NO, NO_x, particulates (Bacharach Smoke Number), and flame radiation (incident on the wall of the combustion chamber). Smoke was undetectable under all conditions, even for the crudes, in this case, probably due to the original water content of the crudes.

Table 4. Test results

Percent water	ϕ	EI_{NO}	EI_{NO_2}	R
Final results, N13				
0	0.75	1.60	2.61	47
10	0.76	1.44	2.20	44
20	0.73	1.17	1.79	35
30	0.75	1.00	1.45	30
40	0.80	0.91	1.26	26
50	0.72	0.95	1.12	25
Final results, 2I44				
0	0.74	1.68	2.61	87
10	0.74	1.50	2.34	74
20	0.74	1.42	2.14	71
30	0.73	1.08	1.66	52
40	0.75	1.03	1.58	37
0	0.61	1.83	2.81	47
10	0.62	1.60	2.49	47
20	0.60	1.44	2.24	44
30	0.62	1.11	1.70	44
40	0.61	1.05	1.60	20
Other results, N13				
0	0.70	1.61	2.59	48
10	0.63	1.50	2.25	32
20	0.67	1.20	1.82	24
30	0.65	1.15	1.48	26
40	0.69	1.03	1.20	24
50	0.52	1.03	1.15	20
40	0.32	1.30	2.30	12
50	0.44	1.17	1.88	16
Other results, 2I44				
0	0.78	1.60	2.70	66
10	0.76	1.42	2.38	62
30	0.75	1.01	1.62	42
50	0.61	0.86	1.12	20
50	0.62	1.03	1.38	25
50	0.53	0.90	1.10	—

Notes: EI_{NO} in g NO/kg oil; EI_{NO_2} in g NO₂/kg oil; radiation R in kW/m²; water content not taking into account the original water content of the fuels; "other results" are selected data from previous series at flow conditions close to the final series.

Table 3. Fuel flow rates

Percent water	Percent corrected	Flow rate (g/min)
N13		
0	6.4	53
10	15.8	60
20	25.1	68
30	34.5	79
40	43.8	93
50	53.2	113
2I44		
0	2.2	50
10	12.0	56
20	21.8	64
30	31.5	75
40	41.3	88
50	51.1	107

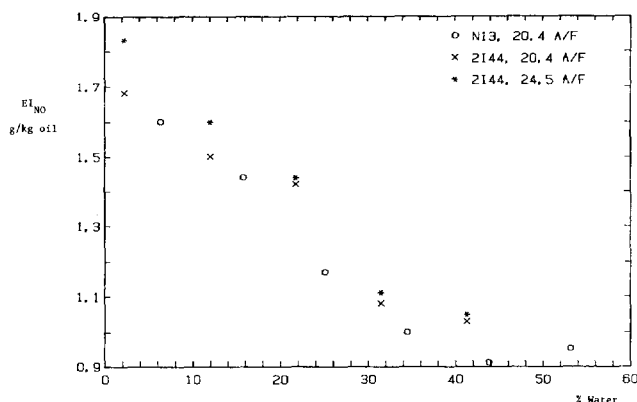


Figure 3. Emission index of nitric oxide (as NO)

Surprisingly, unburned hydrocarbons were more or less constant very near the lower detection limit of the equipment (about 30 ppm as propane), and they are considered to be insignificant. Evaluation of the exhaust gases by smell (more or less involuntary) indicated the obvious presence of hydrocarbons; the intensity of the smell was quite in keeping with the low levels measured. Carbon monoxide levels were even more surprising since they were consistently below the detection limit (on a 0 to 0.5 percent scale).

Because of these surprising results, the gas analysis equipment was very carefully checked for leaks and other possible sources of errors. None could be found. Tests using the same equipment for a single cylinder piston engine showed quite normal levels of CO and H/C. Tests using a different CO/CO₂ measuring setup confirmed again the low level of CO.

Substantial difficulties were encountered with the fuel metering, the calibration of all fuel meters being sensitive to pressure levels. Two different capillary meters as well as a mass flowmeter showed that calibration at low pressure was incorrect at normal injection pressures. Explaining the behavior of the capillary meters by the compressibility of tiny air bubbles entrapped in the emulsion seems to be excluded since microscopic observation showed only negligible evidence of such bubbles. Also, the mass flowmeter used showed similar deviations, even though it was supposed to be insensitive to air bubbles. No rational explanation was found and, eventually, calibration had to be performed at actual system pressures.

Mass flow rates were set at 50 g/min of crude 2I44, i.e., 49 g of water-free oil. This leads to the flow rates shown in Table 3. The two air-flow rates used were 1 kg/min and 1.2 kg/min, leading to nominal air/oil ratios of 20.4 and 24.5 respectively. The results of the tests are indicated in Table 4 and Figures 3 to 5.

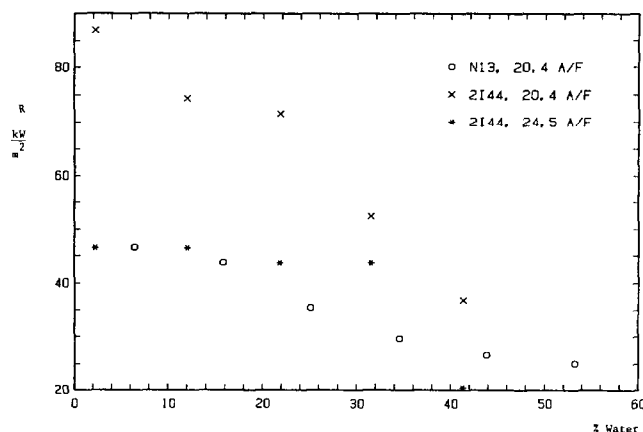
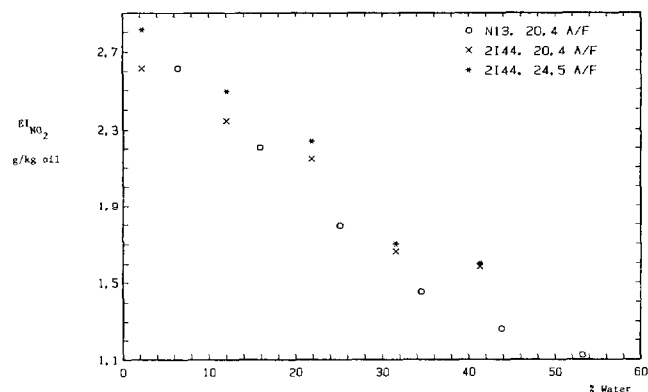


Figure 5. Radiation from the flame

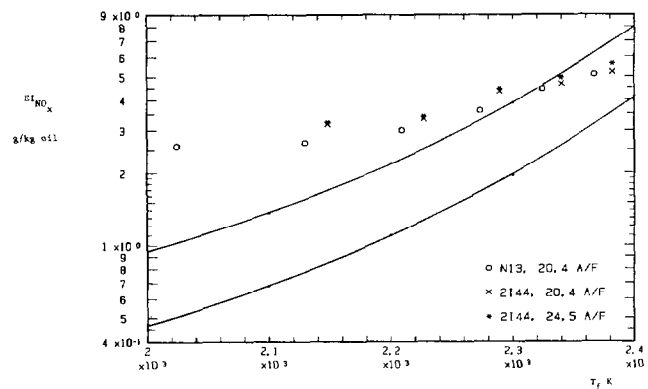
Figure 4. Emission index of NO₂

Discussion

Evaluation of the gas analysis results (along with earlier results not reported here) indicate an atomic H/C ratio for N13 of $2.12 \pm 0.28 - 0.24$, and for 2I44 of $2.08 \pm 0.28 - 0.4$. Assuming these values, the stoichiometric air-oil mass ratios become 15 and 14.9 respectively. These values were used to determine the equivalence ratios in Table 4.

Measured values of emission indices of NO (as NO) and NO₂ indicate the expected decrease with increased water content, a trend seen also in the data from other test series. Also visible is the slight increase with decreasing equivalence ratios, which has been noted elsewhere. Emission levels for the two crudes are similar. The last two points in the "other data" in Table 4 do not line up with the rest of the data, probably due to too much difference in flow rates. While the trend of decreasing emission rates with increasing water content is real, the effect is not as great as expected. Figure 6 shows a plot of the NO_x emission index (as NO₂) against maximum flame temperature assuming stoichiometric mixture and resulting water vapor completely mixed with the combustion gases. This figure also shows a scatterband of hundreds of results obtained in diverse combustors, diffusion flames, and premixed flames, with and without steam addition. The deviation indicates clearly that during combustion fuel and water are not perfectly mixed, as would be expected from micro-explosions where the fragments of the droplets follow separate trajectories. The results from measuring the incident radiation to the wall also indicate the expected trend with water content and overall mixture richness.

In conclusion, it has been shown that the emulsions to be expected from Beaufort Sea crudes can be burned successfully with a minimum of pollution. Emulsions with greater than 50 percent water content

Figure 6. Emission index of NO_x (as NO₂) as a function of maximum flame temperature

can be expected to separate so rapidly they constitute no problem as long as the emulsions are fed to the burner from the top of the retaining reservoir. The lack of combustion problems makes it obvious that the design of a full-scale combustor can follow well-established guidelines from other fields of combustion experience.

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