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COMBUSTION OF SINGLE CWF DROPLETS OF EITHER PULVERIZED OR MICRONIZED COAL.

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Abstract

This paper reports on new experimental findings on the combustion behavior of coal-water fuels (CWF) consisting of either pulverized coal (average size *ca.* 40μm) or of micronized coal (average size *ca.* 4μm). The former CWF is considered as a fuel in utility boilers to substitute petroleum. The latter is considered as a fuel in diesel engines, gas turbines, etc. There are differences in the physical and chemical properties of these fuels since the size of the coal particles differs by an order of magnitude, the resulting packing factor is unequal and the mineral content is different by an order of magnitude as well, since the micronized slurries are also beneficiated. This work concentrated on the combustion of the solid agglomerated particles that remain upon completion of water evaporation. Experiments were conducted in a bench scale high-temperature drop-tube furnace, electrically heated to gas temperatures of 1450 K. Single CWF agglomerates (200-500μm, in diameter) were introduced in the furnace, and upon ignition their combustion behavior was monitored with a specially developed three wavelength (640, 810 and 998 nm) pyrometer. Results showed that the overall combustion behavior of agglomerates of the same size from the two coal grinds was similar when burned under the same conditions.

INTRODUCTION

An important factor in the preparation and the subsequent use of CWF is the particle size distribution of the constituent coal. The influence of the particle grind size on the characteristics of CWF droplet formation and combustion is governed by many factors, such as - rheology, stability, atomization and burning time of the agglomerate, etc. Regarding the combustion behavior, it was realised quite early on [Law, '79; Holve, '87 (pp. 269-291); Holve, '87 (243-268); Miller, '89] that advantages of fine grinding the coal would be lost due to the agglomeration of these individual particles after the evaporation stage. Law et al. speculated that large grind size particles may lead to an incomplete combustion of the resulting CWF agglomerates. Holve et al. ['87] suggested that finer particle grind may be a desired property for fuel applications in gas turbines and diesel engines (because of need for fast combustion times). Use of CWF in power plants may not require this additional fuel preparation. Benedick and Wilson ['90] found satisfactory engine performance with coal particle mean size in the range of 2 to 12μm (with top size of 5 to 65 μm respectively). They also concluded that particle size distribution will most likely be governed by coal cleaning requirements, as coal particle size is closely related to final ash content and energy recovery. Beneficiation also influences the top size of the particle/agglomerate due to higher swelling generally observed for beneficiated coals.[1] Any advantages that smaller grind may have, however, will be lost if the atomizer cannot limit the top size of the CWF agglomerate produced.

Hargrove et al. ['84] studied various CWFs made of different coals and coal particle size distributions (Coal MMD varied from 15-50 μm and Spray Droplet MMD from 72-106 μm). For different firing rates and flame temperatures they did not find much difference in carbon conversion of the CWF. Walsh et al.['84] (similar to Farmayan et al. '84) on the other hand found that (under turbulent flow conditions) carbon conversion was lower for micronized slurry (mean particle size $\approx$ 18 μm) compared to utility grind slurry (mean particle size $\approx 32\mu$m). They also found that the gas temperature and the particle cloud temperature profiles along the length of the furnace for the two cases of micronized slurry and utility grind slurry was not much different though. Murdoch et al. ['84] however found that for single suspended particles burning at wall temperatures of $\approx$ 1373 K, there was an increase in peak temperatures by about 4.5% when the particle grind size was decreased from $95\pm5\mu$m to $36\pm3\mu$m. In the free falling case CWF droplets with smaller coal grind burned in a shorter duration.

From the above it appears that the previous work on the effects of coal grind on the combustion of CWF is inconclusive and at times contradictory. Hence, in this investigation we attempted to resolve this matter by continuously monitoring the combustion of pre-weighed agglomerates of known size made from two distinctly different coal grinds.

EXPERIMENTAL APPARATUS & PROCEDURE

Agglomerate Properties and Preparation. Two different bituminous coals were used in this study with different grind size. A micronized coal water slurry with a mean particle size of 3.5 μm (obtained from Otisca) and a pulverized HVA-bituminous coal (PSOC-1451) with a grind size in the range of 30-45 μm. Thus the particle size in the resulting CWF agglomerates differ by an order of magnitude. The micronized and beneficiated coal contains 61.5% fixed carbon, 37.5% volatile matter and 0.94% ash. The pulverized coal contains 51.9% fixed carbon, 34.43% volatile matter and 13.67% ash.

All slurries were prepared with 1 wt% of ammonium lignosulphonate surfactant. The solid ratio for the as received and initial slurries was 50 wt%. The slurries were in most cases diluted to a solid loading of approximately 40 wt%. As mentioned in Atal & Levendis ['93], for ease of droplet production and subsequent agglomerate formation most of the water was replaced by acetone. Agglomerates were produced by drying slurry droplets in a two-stage tubular thermal reactor [Levendis & Panagiotou '91]. The droplet generator used in this process was positioned at the top of the reactor and a flow of nitrogen was maintained at wall temperatures in the range of 600 to 650°C. The temperature profile was fine-tuned so that agglomerates were collected immediately upon completion of water evaporation (i.e. wet particles were avoided). The agglomerates were thus kept at a fairly low temperature (at

[1] According to Nsakala et al. swelling not only depends on beneficiation but also on the beneficiation method used.

approximately the boiling point of acetone). The droplets travelled the length of the reactor at gas heating rates of ≈20 K/s and the dried agglomerates were collected at the bottom on glass fiber filters. SEM photographs of dried micronized and pulverized agglomerates are shown in Fig. 1 a and b, respectively.

The diameter of each agglomerate was first measured under an optical microscope. Most of the agglomerates were spherical in shape. In case of non-spherical agglomerates the diameter was measured in two perpendicular directions and the calculated mean of these values was used as the diameter. The agglomerate was then transferred to a *Mettler M3* microbalance to obtain it's weight. The sensitivity of the microbalance was 1 μg. The density of the agglomerates was then calculated assuming a spherical agglomerate of known diameter and weight. To calculate the density of the devolatilized chars in the combustion experiments it was assumed that all the volatilcs had burnt during the devolatilization stage.[2]

Combustion studies of free falling CWF agglomerates were conducted in an externally heated laminar-flow furnace [Levendis and Atal '92]. The main radiation cavity of the furnace is a high purity alumina tube which has a diameter of 7 cm. The radiation cavity is 25 cm long and is heated by molybdenum disilicide elements. The required gas mixture is introduced into the radiation cavity through a water-cooled injector and also through a flow straightener which is coaxial to the furnace injector. The furnace injector is a tube of 1.25 cm i.d and is 61.0 cm in length. The pre-dried CWF agglomerates are introduced from ports at the top of this furnace injector. The injector is designed to enable pyrometric observations from the top and also to block direct radiation from the hot furnace walls. The air entering through the flow straightener is preheated in the initial stage of the alumina tube before it reaches the main radiation cavity. Axial and radial gas temperature profiles in the radiation cavity were obtained using suction pyrometry. The centerline gas temperatures for both the furnaces were about 50°C lower than the wall temperatures, except at the tip of the injector where even lower temperatures were recorded [Cumper '90]. CWF agglomerates in the size range considered burn far away from the tip of the injector and thus the local gas temperature surrounding the burning agglomerates can be considered to be constant approximately constant at 1450 K for wall temperatures of 1500 K. For all the experiments the flow rate through the furnace injector was kept at 0.1 lpm and through the furnace flow straightener at 2.0 lpm. This combination of flow at wall temperatures of 1500 K results in gas velocities of 4.55 cm/s and a gas residence time of 5.5 s.

A three-color near infrared pyrometer [Levendis et al. '92] was used to obtain the complete combustion history of the agglomerates. The three interference filters used had working wavelengths of 0.64, 0.81 and 0.998 μm and a bandwidth (FWHM) of 70 nm. Silicon photodetectors were used for all the three channels. The current output was converted to voltage and this was amplified 10^6 times by means of linear amplifiers. In case of weak signals, a second linear amplification stage (of $\times 10$ or $\times 100$) was sometimes added. The time constant for the circuit was less than 1 ms. The pyrometer was calibrated by means of a NIST

[2] Although there is evidence to this fact, McHale et al. '82, to suggest that some volatiles may still exist in the residue/ash collected at the end of char combustion.

pre-calibrated tungsten halogen lamp.

The amplified signals were monitored simultaneously by a *Data Translation* DT2828 A/D high speed board, at a frequency of 33 kHz per channel, and also an oscilloscope. Data was recorded by an IBM-AT 8 MHz, 2.64 MB RAM microcomputer with the aid of the *Asyst* software.

EXPERIMENTAL RESULTS AND DISCUSSION

Complete combustion of a CWF droplet can be divided into four stages: evaporation of the liquid portion, heatup of the agglomerate so formed, release and homogeneous combustion of the volatile phase and finally the heterogeneous combustion of the remaining char. In this study only the latter two stages were studied for different CWF agglomerates.

In order to study the pyrolysis and the physical transformations associated with the volatile release, experiments were performed on agglomerates injected in the furnace at wall temperatures of 1500 K, in an atmosphere of nitrogen. To detect presence of oxygen the exit gas was monitored by an oxygen analyzer (*Beckman, Model 755*). No oxygen was detected when a 99.9% pure nitrogen was used.

The pyrolysis of both types of CWF agglomerates was overall similar. Upon entering the radiation cavity both types of CWF agglomerates heated up which lead to release of the volatile component and at the same time softening and melting of the agglomerate component was induced, which is to be expected for bituminous coals. Some blowholes were created by the escaping gases while some of the pores were closed due to the melting and softening of the char. It is interesting to note here that the pulverized grind coal exhibited both individual coal particle as well as agglomerate swelling and cenosphere formation. The whole agglomerate swelled with a calculated mean swelling factor[3] of 1.12 and 1.05 for the micronized and pulverized coal agglomerates, respectively.

Studies on the combustion of CWF agglomerates were conducted in air at T_g of 1450 K. Combustion of both types of agglomerates can be divided into two distinct phases - the homogeneous combustion of the volatiles followed by further char heatup and combustion. On the intensity-time plot, see Figs. 2 and 3 the volatile phase combustion is indicated by the sharp initial peak. The long hump that follows is the char combustion phase. Many different pre-weighed CWF agglomerates of known size and, thus, known density were burned and the results are tabulated in Table I and II. Two typical intensity-time and temperature-time profiles of a micronized and a pulverized grind CWF agglomerate are shown in Figs. 2 and 3, respectively. From these two figures it can be seen that the combustion behavior of the two equal size agglomerates is similar, both in the volatile and in the char combustion stages. This can also be confirmed by comparing combustion temperatures and durations for particles of similar size in Tables I and II. There are density variations from agglomerate to agglomerate of the same coal grind as well as different coal grinds that make absolute comparisons difficult, but overall the burning times and temperatures are similar and those of the char are very

[3]It can also be assumed that for the high solid loadings used in these experiments that the diameter of the CWF droplet is the same as the diameter of the CWF agglomerate formed after drying. Thus, the swelling factor represents the ratio of the swelled char diameter to the CWF droplet.

TABLE I

Combustion of micronized CWF agglomerates

Dia (μm)	File	Weight (μg)	Density (g/cm^3)	T_w (K)	% O_2	Time (volatile)	Temp (volatile)	Time (char)	Temp (char)
270.0	mcaw14	6	.5822	1500	21	37	2500	281	1975
292.5	mcaw15	8.5	.6487	1500	21	38	2450	275	1950
300.0	mcaw12	11.5	.8135	1500	21	47	2450	366	2000
322.5	mcaw11	13	.7402	1500	21	52	2500	382	2100
348.75	mcaw13	15.5	.6979	1500	21	66	2550	500	2100

TABLE II

Combustion of pulverized CWF agglomerates

Dia (μm)	File	Weight (μg)	Density (g/cm^3)	T_w (K)	% O_2	Time (volatile)	Temp (volatile)	Time (char)	Temp (char)
225.0	psaw24	3	.5030	1500	21	28	2500	236	2200
247.5	psaw23	6	.7558	1500	21	34	2350	272	2000
270.0	psaw18	9	.8733	1500	21	36	2500	265	2000
285.0	psaw22	8.5	.7013	1500	21	40	2500	280	2100
315.0	psaw31	15	.9166	1500	21	51	2450	322	2100
330.0	psaw13	15	.7972	1500	21	59	2500	367	2000
337.5	psaw14	15	.7452	1500	21	58	2500	373	2100
360.0	psaw12	17	.6959	1500	21	61	2500	400	2100
405.0	psaw8	25	.7188	1500	21	83	2500	465	2200

close to the predictions of simplified molecular diffusion control models [Field '67; Atal '93]. This indicates that the agglomerates of the size range employed herein burn in Regime III, under the conditions of this study (air, $T_w = 1450$ K). This fact in combination to the melting and cenosphere formation, as well as the fact that catalytic effects of the ash are weak at the high temperatures encountered, mask any substantial differences that the coal grind size (or even the different ash content may have). There are minor differences, however. Careful examination, for instance, can show that the pulverized coal agglomerates are usually denser and burn at a little faster than those of the micronized coal. Thus, the apparent rate of the former is somewhat higher.

The volatile flame duration and temperatures are also similar since both coal types contained the same amount of volatiles.

SUMMARY

Fundamental studies on the combustion of single coal-water fuel agglomerates consisting of either micronized or pulverized bituminous coal grinds have been undertaken. These studies were conducted with pre-dried CWF agglomerates of known initial size and weight. The combustion behavior, the particle (agglomerate) temperature and the particle burntime were monitored with ratio optical pyrometry. It was found that CWF agglomerates in the size range of 200-500μm burn with two distinct phases of volatile flame combustion (10-20% of the total time) and char oxidation. The volatile flame temperatures exceeded the furnace gas temperature by approx. 1000 K and the flame duration varied according to the agglomerate size. Same size agglomerates from the two coal grinds of this study generated volatile flames of comparable durations, since the volatile content of the two coals was similar. Char temperature and burntimes were found to depend strongly on the agglomerate size. The influence of the coal grind on the char combustion was weak, the pulverized grind agglomerates burned slightly faster in most cases.

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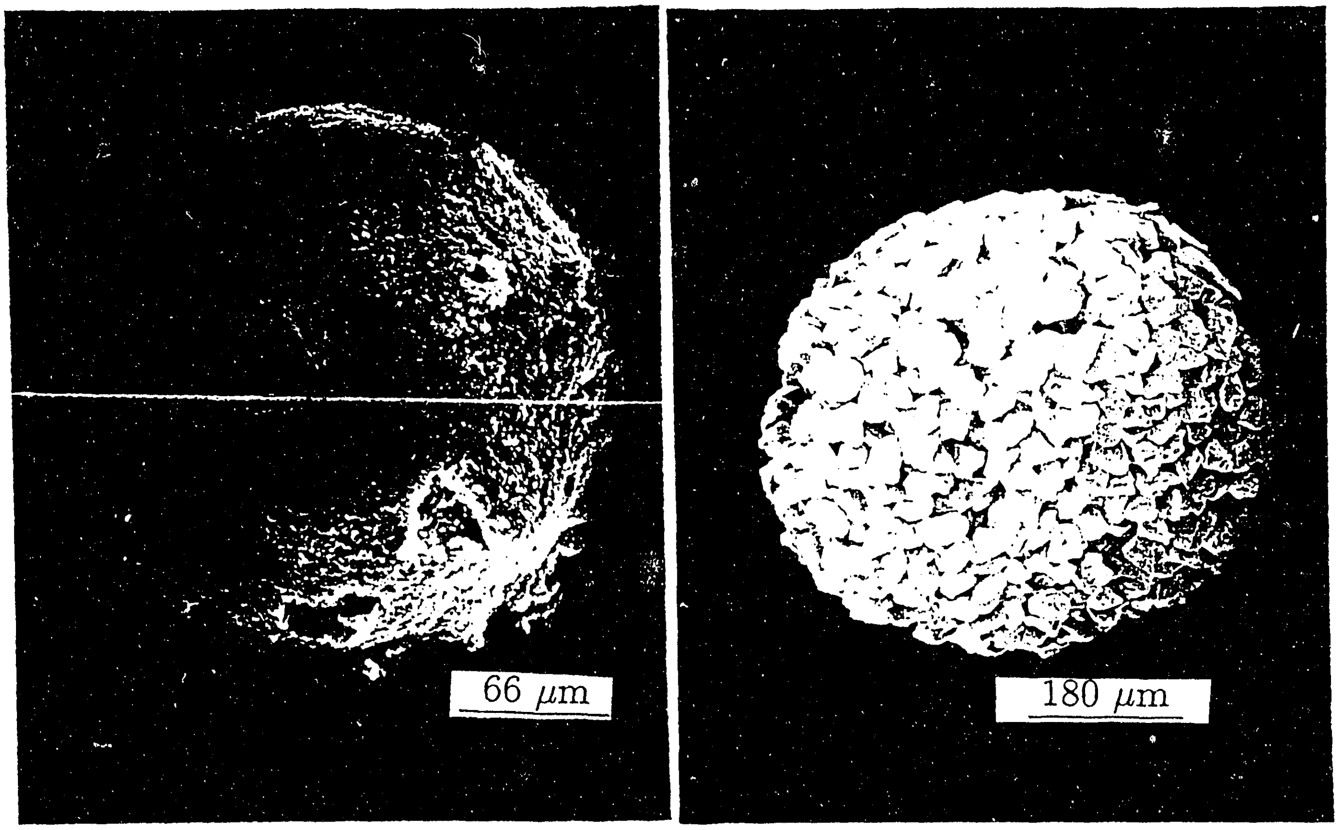


• FIGURE 1. (a) SEM photograph of a dry micronized CWF agglomerate with diameter ≈250μm; coal grain ≈3.5μm. (b) SEM photograph of a dry pulverized CWF agglomerate with diameter ≈585μm; coal grain ≈40μm.

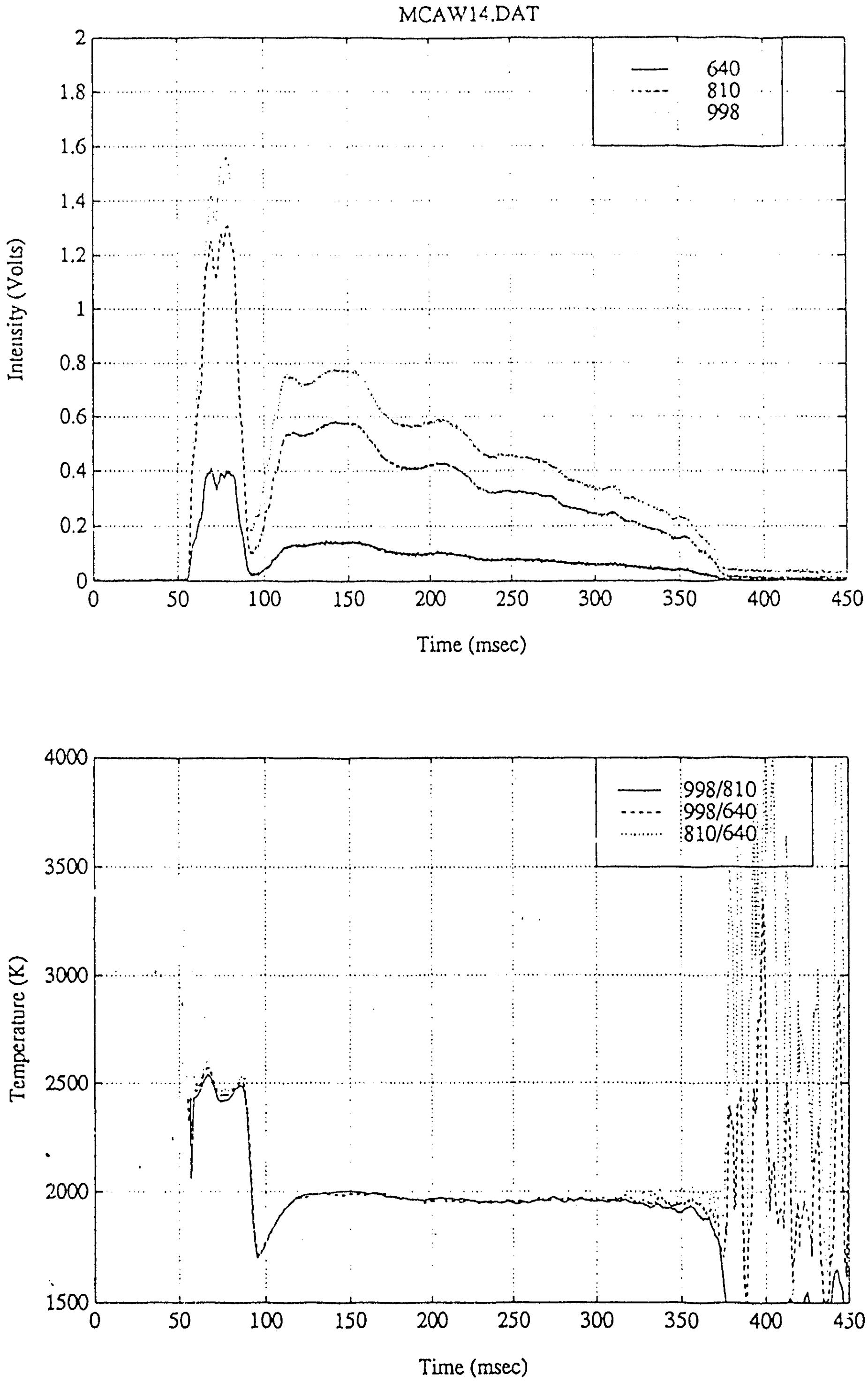
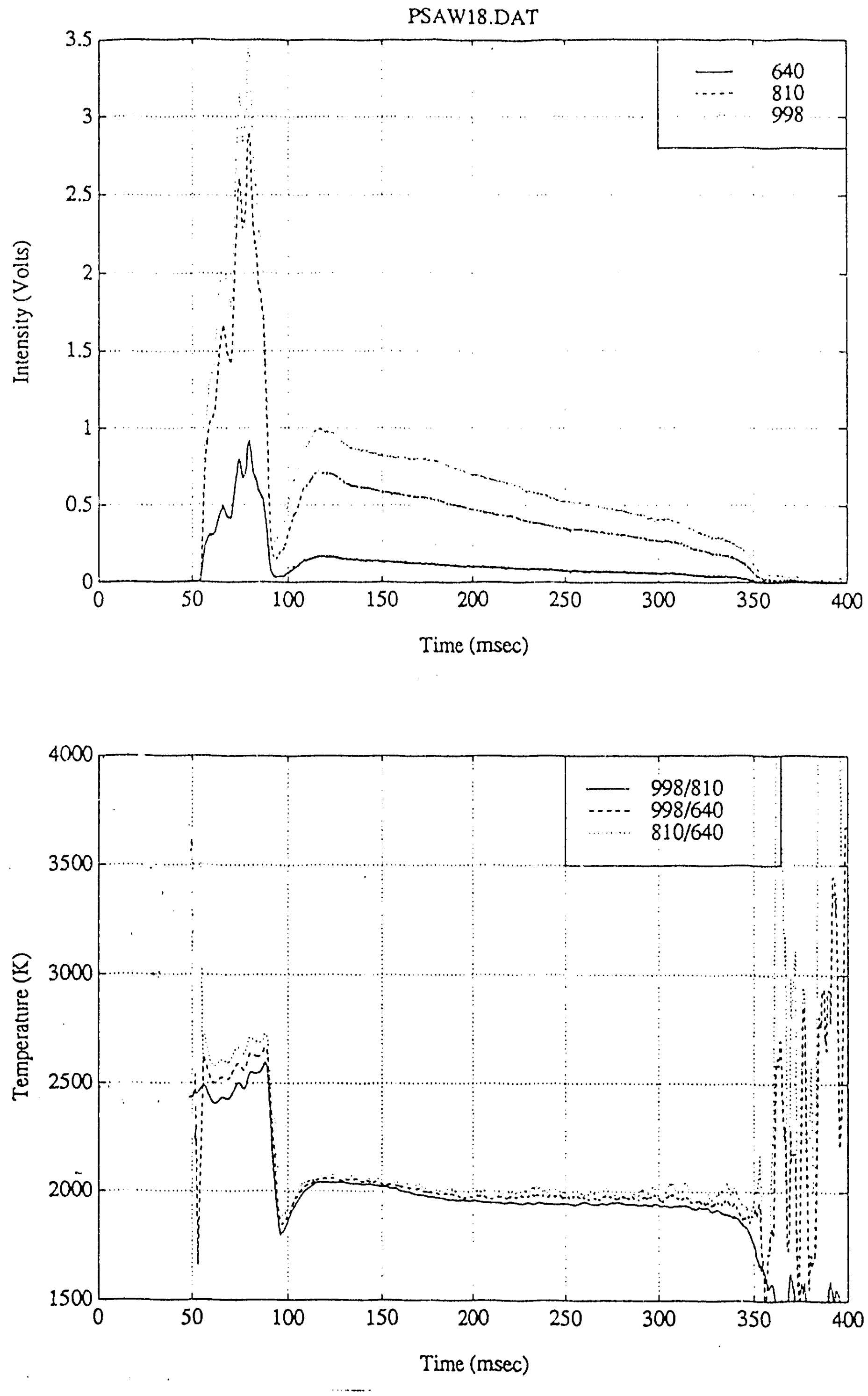


FIGURE 2. Three-color pyrometry intensity signals (top row) and two-color ratio temperature profiles (bottom row) for a micronized CWF agglomerate, with initial diameter $\approx 270 \mu m$, burning in air at T_g of 1450 K, $\rho_a = 0.58$ g/cm^3.



• FIGURE 3. Three-color pyrometry intensity signals (top row) and two-color ratio temperature profiles (bottom row) for a pulverized CWF agglomerate, with initial diameter $\approx 270 \mu m$, burning in air at T_g of 1450 K, $\rho_a = 0.87$ g/cm^3.

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