Cost analysis of conductive carbon nanoparticle production *via* high-temperature premixed stagnation flames

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Abstract:
High-temperature premixed stagnation flames may provide unique advantages for carbon black production even though this is a readily available commodity which is already integrated into many technologies (e.g batteries and supercapacitors). This particular flame configuration allows for the smallest carbon particles to be synthesized in a relatively high-temperature environment and this results in high-surface area conductive particles. Cost analysis will be carried out for this process and compared to existing methods of conductive carbon production. As is the case with most flame-based production methods, stagnation flames are scalable and there is potential for this method to compete with existing industrial conductive carbon methods, especially considering the potential for economical, energy efficient production high-surface area nanoparticles. The throughput of carbon production of the flame is important especially considering that significant excess fuel is required to reach particulate formation conditions in premixed flames. The smallest nanoparticles also require extra consideration in terms of collection onto a substrate or filter due to the high diffusivity and low deposition efficiency.

Keywords:

carbon, devices, conductivity, batteries, supercapacitors, costs, flames, combustion, flame-synthesis.

1. Introduction

Carbon is a versatile material that is used for both traditional and cutting edge applications. More recently, nano-scale carbon has garnered attention due to unique properties attributed to nanotube, graphene and graphite carbon polymorphs. In this work, the prospect for extending flame-based processes of conductive carbon to higher surface area conductive carbon nanoparticles will be assessed. Flame-based processes are already the basis of industrial carbon black production which outputs on the order of 10 Mton / year.

2. Scope and Methods

Electrically conductive carbon requires high carbon purity and a relatively ordered carbon lattice [1]. Conversion of the feedstock to carbon having these properties requires reactor temperatures exceeding 2300K [1]. The premixed stagnation flame configuration [2] will be used in this work because the stretch-stabilization mechanism for the flame allows for a quasi-1D flow field without heat losses to the surroundings. These flame conditions will enable carbon flame synthesis at the required temperatures in a uniform and well-characterized temperature-time history. A typical premixed stagnation flame is shown in Figure 1. High-surface area carbon particles (nano-particles) with narrow size distributions can be readily obtained but the conversion rate of feedstock to particulate carbon is low because only a small fraction of the excess fuel condenses into particles in premixed flames.

Conversion of acetylene in natural gas supported premixed flames is an approach that may mitigate the losses due to unconverted feedstock. Another advantage that this flame configuration holds is the ability to be integrated into *in-situ* hybrid synthesis / fabrication processes. In this work, these two factors will be the focus of cost-analysis for conductive carbon synthesis in premixed flames.

Industrial-scale production of carbon black has been carried out for over a century. Modern carbon black production is dominated by the Furnace Black process (95% of US carbon black) because carbon yield is relatively high. The well-known costs of carbon black production via the Furnace Black process will be compared to analysis carried out in this work.

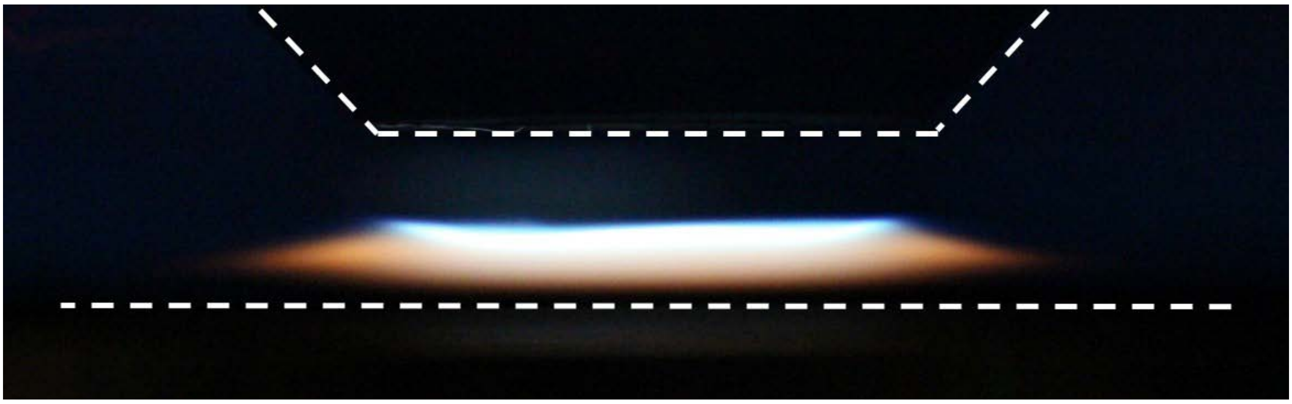

Fig. 1. Typical premixed stagnation flame configuration at carbon formation conditions.

3. Analysis

Sid Richardson Carbon and Energy Co., an American carbon black company, produced 445 kilotons in 2014 [3]. In a recent report [4], Sid Richardson specifies that the required materials to produce 1 kg of carbon black using the Gas Furnace Black process. A simple analysis for the cost of producing 1 kg of carbon black are shown in Table 1. The feedstock in the Sid Richardson Process is no. 6 type fuel oil but the generic heating oil price supplied by the US Energy Information Agency was considered here. Average US prices were also taken from the US Energy Information Agency for natural gas and electricity. The analysis shows that the feedstock cost is the only significant contributor to the production costs.

Table 1. Cost analysis for production of carbon black in the Sid Richardson Gas Furnace process

material	amount / kg product		material cost		cost / kg product ($/kg)
oil	1.6	liters[a]	0.40	$/L[b]	0.63
natural gas	0.3	m^3 -stp[a]	$8.5x10^{-5}$	$/$m^3$[3,b]	$2.6x10^{-6}$
electricity	0.6	kW-hr[a]	0.10	$/kw-hr[b]	0.06
water	5.0	kg[a]	$1.7x10^{-4}$	$/kg[c]	$8.5x10^{-4}$

a. Sid Richarson b. US Energy Information Agency c. Irvine Ranch Water District

Very little work has been carried out concerning the production, much-less cost-analysis of carbon black in premixed flames. However, carbon formation in premixed flames in the form of soot is a mature field of study aimed at optimization of combustion performance and emissions reductions. In this work, production rates of soot from ethylene flames will be used as an estimate for the potential production of graphitized carbon. Similar to carbon black production processes, the cost of the feedstock is expected to be the most significant cost. Previous work by the author [2] has shown that high surface area nano-particles can be produced in premixed flames with a relatively narrow size distribution. However, as Figure 2 shows, the output volume fraction of nano-particulate carbon can be less than 1 part per billion (volume) in premixed flames. The graphite-like structure of nano-particulate carbon products was also reported by the authors [5] for similar growth conditions of the previous work. Example Raman Spectra, shown in Figure 3, indicate that the size of graphite-like planes on the carbon products increases with particle growth temperature.

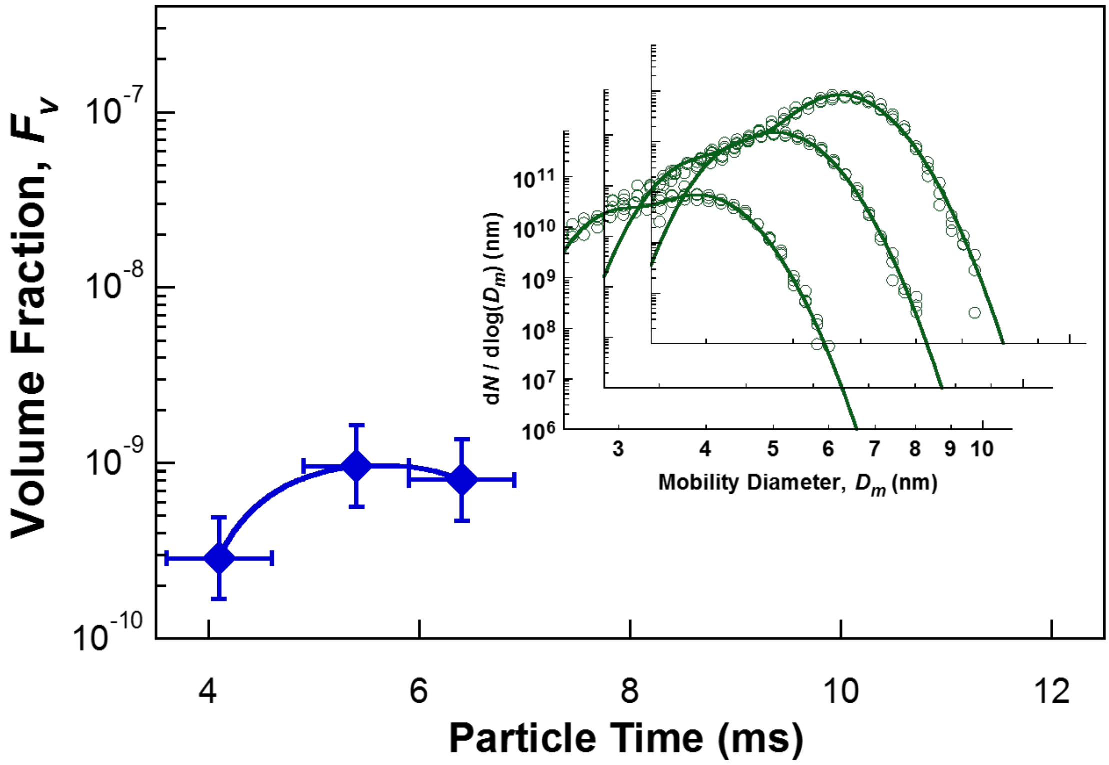

Fig. 2. Measured particle volume fraction and particle size distribution of carbon products for a series in premixed flames reported previously by the author (Flames S3a-c)[2].

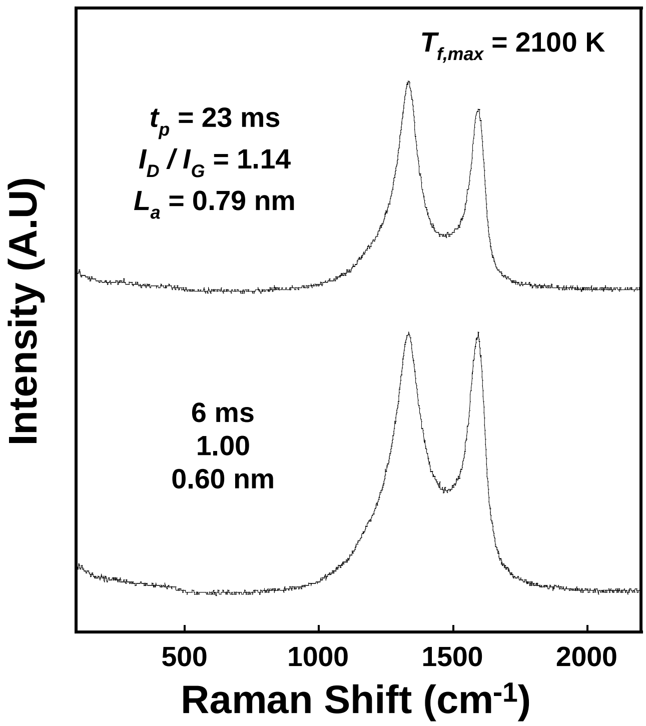

Fig. 3. Raman Spectra reported previously by the author [5] for carbon products deposited from premixed flames with growth conditions similar to Flames S3a-c.

In the current work, the previously reported size and concentration of carbon products from Flames S3a, S3b and S3c in Camacho et. al 2017 will be analyzed for costs. The S3 series of flames is premixed with an equivalence ratio of 2.4 and maximum flame temperature close to 2150 K. The velocity of the flow was varied while keeping the mixture composition constant to provide particle growth times of 4.1, 5.4 and 6.4 ms. The cost of the feedstock ethylene was taken from a recent 11 lb purchase from Airgas which amounted to $8.25/kg. Of course, this non-bulk purchase is more expensive but similar to larger scale operations, the fuel feedstock is the most significant cost.

In the current Analysis, cost of ethylene will be related to the flow rates, particle concentration and particle size of Flame S3 products to determine the associated costs. The resulting analysis is shown in Table 2. As the analysis shows, the cost per kg of carbon particles from the current premixed flames is astronomically higher than large scale conventional carbon black production. This is expected from the nature of carbon particle formation in premixed flames which output what amount to trace amounts of solid carbon.

Table 2. Cost analysis for production of carbon nanoparticles in selected premixed flames.

flame	C_2H_4 cost ($ / (cm^2 min))	solid volume fraction x 10^{10}	flow velocity (cm / s)	solid flux x 10^6 (g / (cm^2 min)	particle cost ($ / g)	median particle size (nm)	surface area density x 10^{-6} (cm^2 / g)	surface area cost x 10^4 ($ / cm^2)
S3a	0.010	2.5	110	2.8	3930	3.9	10	3.8
S3b	0.007	9	84	6.5	1430	5.0	8	1.8
S3c	0.007	8	77	5.5	1755	5.8	7	2.5

4. Conclusion

High-temperature premixed stagnation flames may provide unique advantages for carbon black production even though this is a readily available commodity which is already integrated into many technologies (e.g batteries and supercapacitors). This particular flame configuration allows for the smallest carbon particles to be synthesized in a relatively high-temperature environment and this results in high-surface area conductive particles. The cost of small-scale production of carbon nano-particulates in flames is astronomically higher than the costs of large-scale conventional production. However, the high-surface area and narrow size distribution may justify some of the extra costs. In addition, further work on combining synthesis and fabrication processes incorporating the material may show that premixed flames may have additional benefits in this context.

5. References

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