DIFFUSION AIR EFFECTS ON THE SOOT AXIAL DISTRIBUTION CONCENTRATION IN A PREMIXED ACETYLENE/AIR FLAME

Fábio Luís Fassani   fassani@fem.unicamp.br
Alex Álisson Bandeira Santos   absantos@fem.unicamp.br
Leonardo Goldstein Junior   leonardo@fem.unicamp.br
State University of Campinas
College of Mechanical Engineering, Department of Fluid and Thermal Engineering
Carlos Alberto Ferrari   ferrari@ifi.unicamp.br
State University of Campinas
Physics Institute, Department of Quantum Electronics

Abstract – Soot particles are produced during the high temperature pyrolysis or combustion of hydrocarbons. The emission of soot from a combustor, or from a flame, is determined by the competition between soot formation and its oxidation. Several factors affect these processes, including the type of fuel, the air-to-fuel ratio, flame temperature, pressure, and flow pattern. In this paper, the influence of the induced air diffusion on the soot axial distribution concentration in a premixed acetylene/air flame was studied. The flame was generated in a vertical axis burner in which the fuel - oxidant mixture flow was surrounded by a nitrogen discharge coming from the annular region between the burner tube and an external concentric tube. The nitrogen flow provided a shield that protected the flame from the diffusion of external air, enabling its control. The burner was mounted on a step-motor driven, vertical translation table. The use of several air-to-fuel ratios made possible to establish the sooting characteristics of this flame, by measuring soot concentration along the flame height with a non-intrusive laser light absorption technique.
Keywords – Combustion, Flame, Soot Formation, Laser

1. INTRODUCTION

Sooting in flames has long been studied not only from a scientific viewpoint but also for practical purposes, such as the promotion of radiative heat transfer in boilers and furnaces and the reduction of soot emitted as a pollutant from combustors and diesel engines. Soot are those carbonaceous particulates that form from the gas phase combustion processes; those that develop from pyrolysis of liquid hydrocarbon fuels are generally refereed to as coke or cenopheres (Glassman ,1987).

Haynes and Wagner (1981) commented that soot generated in combustion processes was not uniquely defined. It normally looks black and consists mainly of carbon, but it is quite different from graphite. Apart from carbon, soot particles also contain up to 10% hydrogen (molar basis), and even more when they are young.

Turns (1996) reported soot formation as proceeding in a four-step sequence:

- Formation of precursor species;
- Particle inception;
- Surface growth and particle agglomeration, and
- Particle Oxidation.

C_2H_2 and polycyclic aromatic hydrocarbons (PAH) play an important role in soot formation. Kennedy (1997) commented that the aromatic species grow by the addition of other aromatic and smaller alkyl species to form larger PAH. Continued growth of the PAH leads eventually to the smallest identifiable soot particles. XU et al. (1998) observed that it is generally agreed that soot is mainly formed from C_2H_2, because it is one of the most abundant gaseous hydrocarbon species in regions where soot is formed in laminar premixed flames.

The emission of soot from combustors, or from flames, is determined by the competition between soot formation and its oxidation. Haynes (1991) stated that a high reaction probability that the OH radical dominated soot oxidation in flames exists, even in the presence of significant concentrations of oxygen.

The air-to-fuel ratio effect on soot formation was studied by Roessler et al. (1981), who commented that the morphology of diesel particulate emissions varied strongly with engine operating conditions, such as air-to-fuel ratio. Particles produced at low air-to-fuel ratios were highly agglomerated, whereas at high air-to-fuel ratios the particles were less agglomerated.
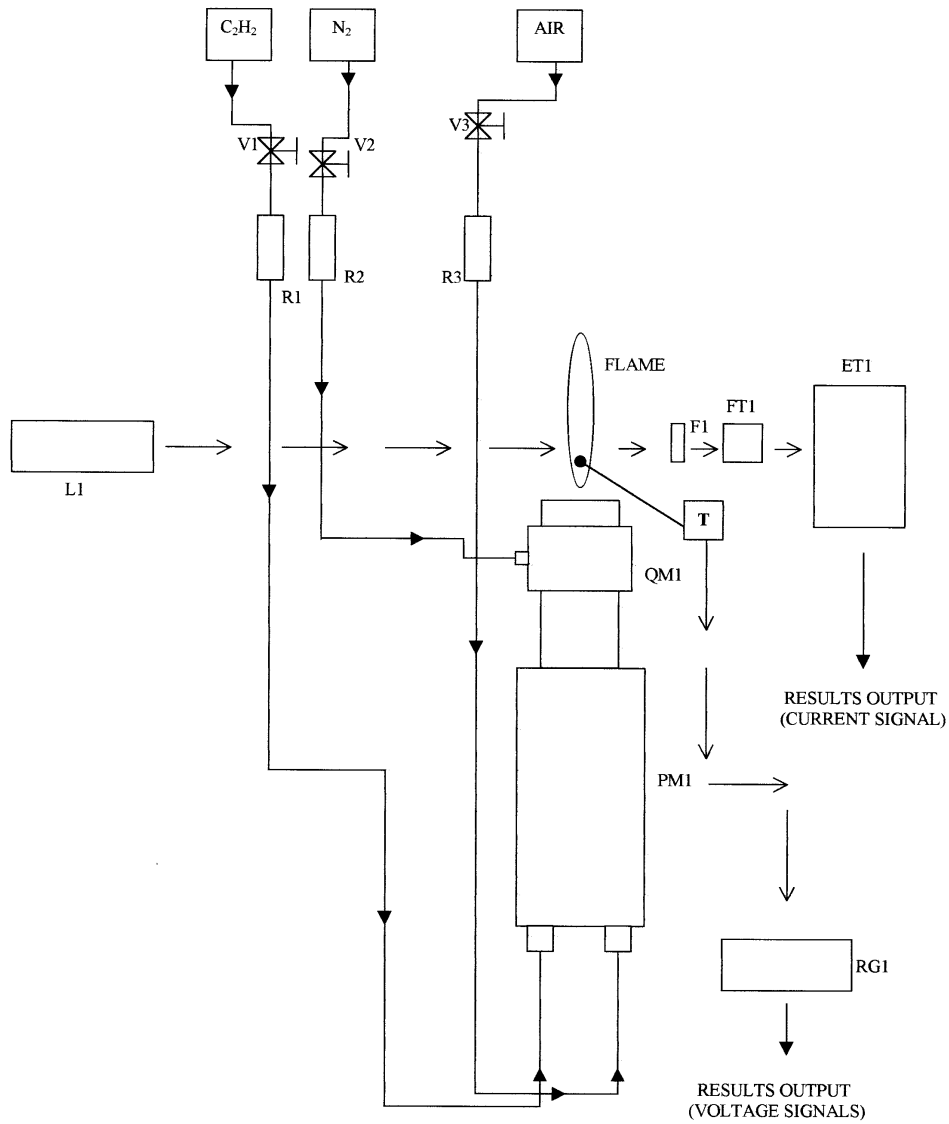
Tolocka et al. (1999) proposed the global equivalence ratio (GER), defined as the moles of carbon divided by the moles of oxygen, normalized by the stoichiometric ratio, as a parameter to characterize soot formation in ethylene / air diffusion flames. Their results showed that the concentrations of soot had a maximum at GER=1.

The purpose of this work is to study the influence of air diffusion on the soot concentration distribution and temperature field in a premixed acetylene / air flame for several premixed air-to-fuel ratios.

2. EXPERIMENTAL

The experimental setup is shown in Fig.1. The flame was generated with a burner in which the fuel and oxidant flow from a vertical tube, and nitrogen flows from the annular region between this tube and a larger diameter concentric tube. The use of nitrogen flows provides a shield that protects the flame from the diffusion of external air. The burner was mounted on a step-motor driven, vertical translation table. Gas flow rates were metered by rotameters.

Soot concentration was measured by laser light extinction. A He-Ne laser with wavelength 632.8 nm was employed. Power output from the laser was only about 1mW, so background radiation from the flame had to be blocked by a narrow band pass interference filter at the laser wavelength. The signal of light was transformed in a electrical current signal by a photo-dyode, and registered by an electrometer.

V1,V2,V3 – VALVES R1,R2,R3 – ROTAMETERS L1 – LASER F1 – FILTER
FT1 – PHOTO-DYODE ET1 – ELETROMETER T – TERMOCOUPLE QM1 – BURNER RG1 – TEMPERATURE METER
PM1 – PREMIXED EQUIPAMENT

Figure 1 - Experimental Setup

Soot concentration was calculated from extinction data using Rayleigh limit of the Mie theory:

$$C = \frac{-\lambda}{6\pi \, \mathrm{Im}\{\frac{(m^2-1)}{(m^2+2)}\}} K_{ext} \qquad (1)$$

$$K_{ext} = \frac{1}{L} \ln\left(\frac{I}{I_o}\right) \qquad (2)$$

where C is the soot concentration, λ the laser wavelength, L the optical path length, I the laser beam intensity after its passage through the flame, and I_0 the laser beam intensity before the flame, and m is the refractive index, adopted as m = 1.90-0.55i (Lee and Tien , 1981).

The flame temperature was measured by a type S termocouple (Pt-Pt/10%Rh). The thermocouple results were not corrected for radiative losses in view of the uncertainty in its value, due to soot deposition on the thermocouple surface.

Laser light extinction and temperature were taken along the vertical axis of a premixed acetylene/air flame. The thermocouple bead was always inserted in the central axis of the flame. Some preliminary work was necessary to find the flow rate to obtain a steady flame. Both flash back and flame lift were observed out of these conditions. In some cases the occurrence of a small explosion was noted. All the measurements were taken at a fixed total flow rate (air + acetylene) of 0.3 Nm^3/h, at air-to-fuel-ratios of 1.4, 2.0, 3.0 and 5.0. Tests were performed with and without a nitrogen shield, enabling the assessment of the external air diffusion effects. To preserve the flame stability, it was necessary to use the same flow rate in the nitrogen shield.

3. RESULTS AND DISCUSSION

Figures 2 and 3 show the soot concentration variation with air-to-fuel-ratio (A/F) in four heights above burner (H.A.B.), at the two flow conditions, namely, with and without the nitrogen shield.
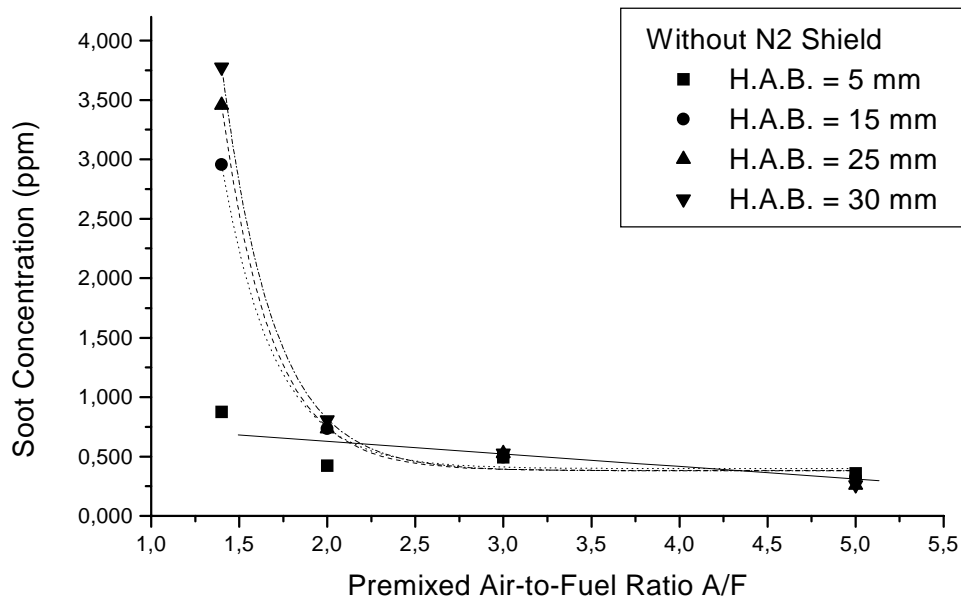

Figure 2 - Soot concentration against air-to-fuel-ratio. Tests without the nitrogen shield.

Soot formation is reduced when there is oxygen induction, i.e., when there is no nitrogen shield. For low values of the air-to-fuel-ratio, soot formation takes place all over the flame. Increasing the air-to-fuel-ratio leads soot to form close to the burner, so that when A/F $\geq$ 3 the formation process occurs essentially at the flame base. This conclusion is supported by the observation of the concentration profile above this ratio in both graphs, which stayed leveled at a

constant value. One could argue that the induced oxygen could oxidize the soot, balancing its concentration, but the same phenomenon occurred when the oxygen induction was avoided, by introducing the nitrogen shield. This fact is an evidence that the amount of soot formed at the flame base remained unchanged throughout the flame height.   Moreover the premixed A/F = 3 is a condition in which the flame is basically isotherm.
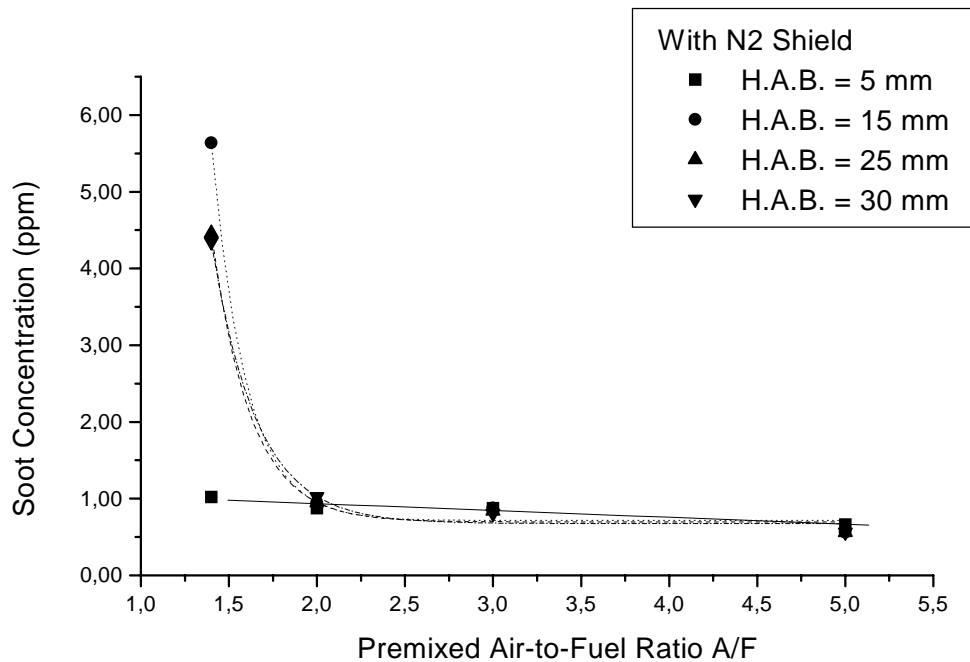

Figure 3 - Soot concentration against air-to-fuel-ratio. Tests with the nitrogen shield.

The temperature behavior is shown in Figs. 4 and 5. It is observed that in any height above 15 mm the temperature variation with the premixed air-to-fuel ratio reaches a maximum at A/F=3, for a given flame height, possibly due to the flame shortening, caused by the higher oxygen availability, leading to higher temperatures at lower positions. This observation is in close agreement with the general premixed flame temperature profile depicted by Borman and Ragland(1998). A subsequent increase in the premixed air-to-fuel ratio caused a flame temperature decrease, mainly due to the higher premix dilution.

In the position 5 mm above the burner, the temperature distribution had an opposite trend, possibly because this point was situated inside or nearby the inner cone of the flame. When the flame was rich, the inner flame cone tended to be thin, so that it was close to the flame front, where temperatures are higher. The increase of the air-to-fuel ratio for this flame caused the inner cone to become thicker, enabling its central region to be comparatively colder, since it was further away from the flame front. Finally, an additional increase in the ratio made the inner cone even thicker and shorter, so that the 5 mm position in question was now outside the inner cone, in a region where temperatures were higher.
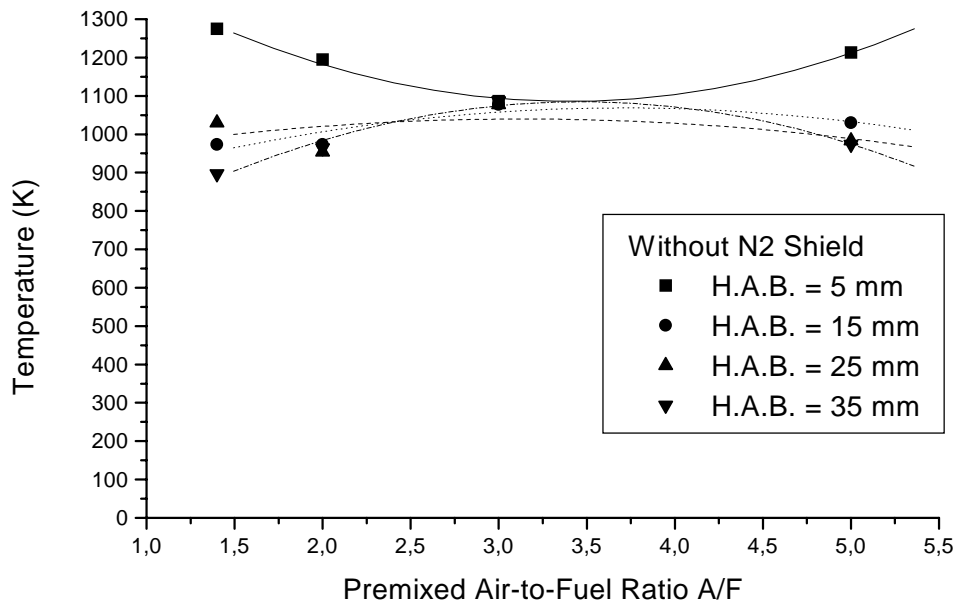
Figure 4 - Flame temperature as a function of the air-to-fuel ratio. Tests without the nitrogen shield.
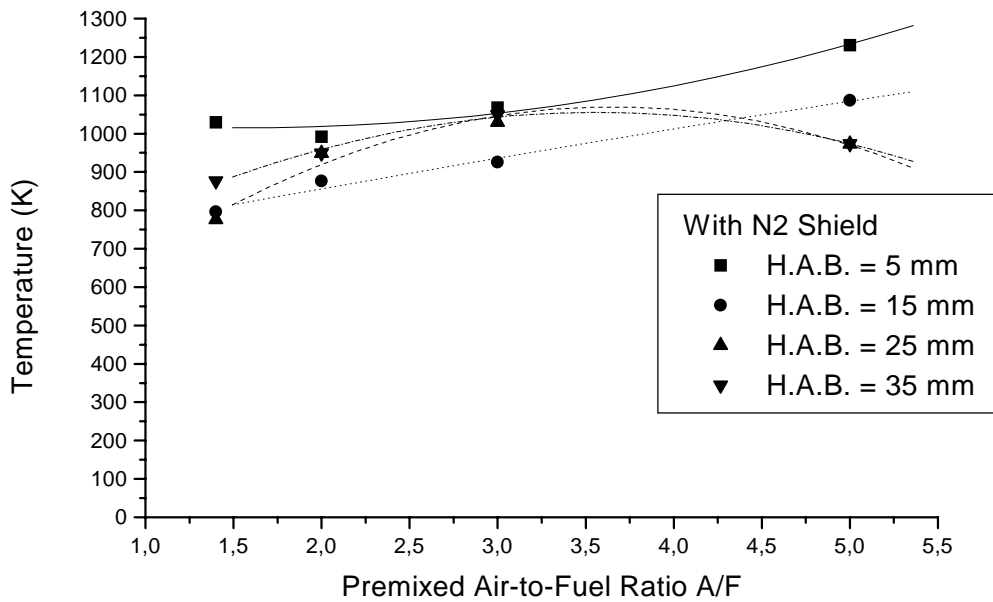

Figure 5 - Flame temperature as a function of the air-to-fuel ratio. Tests with the nitrogen shield.

A typical curve of soot concentration against the height above the burner is shown in Fig. 6, where results obtained with and without the nitrogen shield are compared.
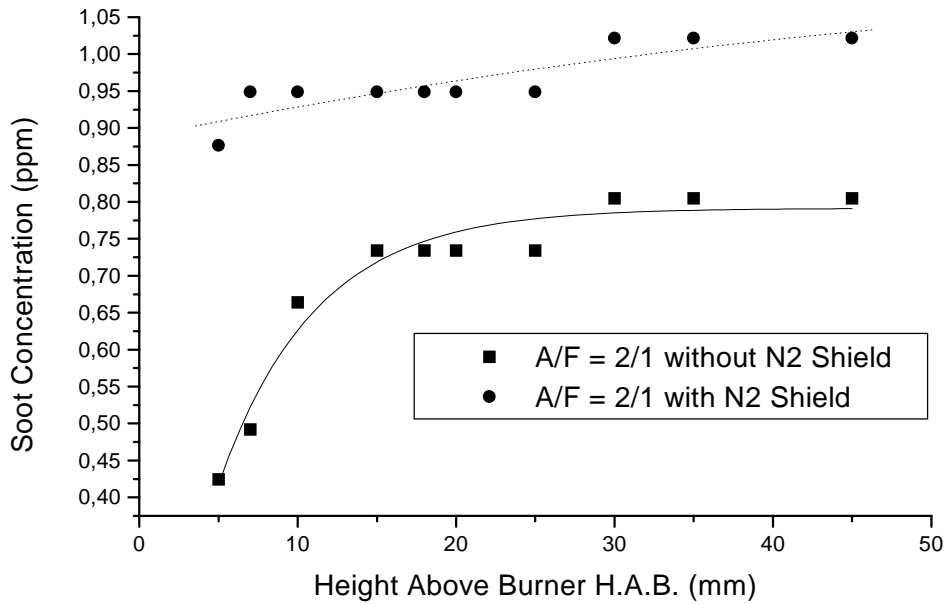
Figure 6 - Soot concentration above the burner

For this air-to-fuel ratio, there was an increase in soot concentration with increasing height. As stated before, this result shows that soot formation took place all over the flame in this condition. The use of the nitrogen shield blocked the diffusion of external air into the flame, thus causing an increase in soot concentration, mainly due to a reduction in the oxygen available to burn the acetylene. In addition, there was a flame temperature decrease near the burner when nitrogen was employed, as one can see in Fig. 7, which presents the temperature distribution for the same test; as observed by Turns (1996), a temperature decrease favors soot formation.
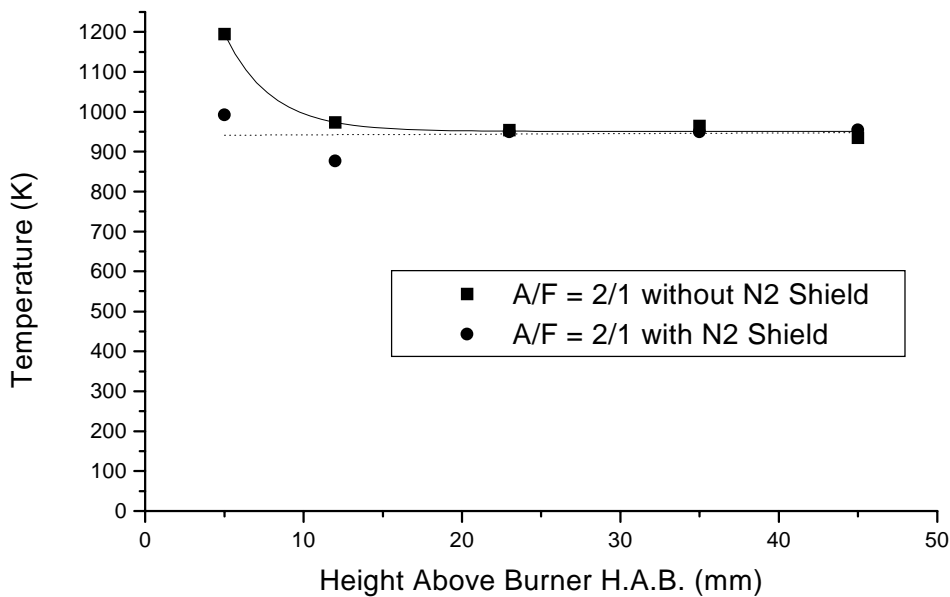

Figure 7 - Flame temperature distribution

4. CONCLUSION

In this paper the effect of air diffusion on the soot concentration in a premixed acetylene/air flame was studied, for several air-to-fuel ratios. It was confirmed that the oxygen induced into the flame causes a reduction in soot formation.

It was shown that soot formation took place all over the flame for low values of the air-to-fuel ratio. For air-to-fuel ratios greater than 3, where the flame was essentially isotherm, it was concluded that the formation process occurred mainly at the flame base, a phenomenon whose observation was made possible by controlling the oxygen diffusion to the flames, by surrounding it with a nitrogen shield.

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