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RESEARCH MEMORANDUM

COMBUSTION OF SMOKE IN DIFFUSION AND BUNSEN FLAMES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

Varying amounts of smoke, both in the form of concentrated filaments and dilute homogeneous mixtures with the combustible, were burned in diffusion flames of ethylene and in Bunsen flames of ethylene-air mixtures. Stable flames of both types were found capable of burning large amounts of carbon smoke if the smoke was finely divided.

It was found that finely divided smoke passing through the flame zone in the form of a laminar filament could be completely burned at a relative smoke-fuel carbon ratio within the filament as high as 3.5:1. Conversely, low over-all concentrations of smoke could pass through the reaction zone without burning completely, if the smoke was agglomerated into flecks of soot. The smoke was found to burn in both the inner and the outer cones of the Bunsen flame.

INTRODUCTION

This report deals with a NACA Lewis laboratory study of the combustion of smoke in diffusion and bunsen flames of ethylene. The experimentation discussed in this report was performed to determine whether smoke added to a combustible mixture from an outside source could be burned in the reaction zone of a flame. The question of whether smoke will burn completely in the reaction zone of a flame has an important bearing on the direction of combustion-chamber research aimed at preventing smoking. If smoke does not burn in the flame, the emphasis in combustion-chamber research should be on the suppression of the formation of smoke. If smoke does burn in a flame, a second line of attack is also possible; namely, the determination of the most efficient method of burning the smoke generated.

APPARATUS

The apparatus used in this series of experiments is shown in figure 1. The lower smoke lamp burning a liquid fuel was so constructed that the inner fuel container and wick holder could slide in the outer housing containing the air ports and the wick shield. A screw adjustment allowed the inner container to be adjusted relative to the outer sleeve so that different flame heights and thus different amounts of smoke could be obtained from the lamp. The lamp flame was shielded from drafts by a glass housing open at the bottom. A glass tube 60 centimeters long and 12 millimeters in internal diameter, with the upper end constricted into a nozzle, was mounted directly above and co-axial with the smoke lamp. This tube formed a chimney for the hot gases and smoke from the lamp. Two side tubes were attached to the lower end of the large tube to supply ethylene and air for the flame, which was ignited at the nozzle of the large tube.

PROCEDURE

Generation of Smoke-Burning Flames

Smoke for this series of experiments was supplied by a wick lamp burning a liquid hydrocarbon fuel. The lamp flame smoked when the flame height was increased beyond a centimeter. The amount of smoke generated by the wick-lamp flame could be varied by varying the flame height. This smoke was directed into the base of the burner tube, which acted as a chimney. The smoke drifted up the tube in the form of a laminar filament. When fuel for the upper burner was added through a side tube, it was possible to keep the smoke stream intact by injecting the fuel gas upward with a small nozzle in a direction parallel to the smoke flow. If the fuel gas was injected directly at right angles to the smoke stream or if air was injected by either method in large enough quantities to form a Bunsen flame with the fuel burning at the top of the tube, the smoke stream was disrupted by the turbulent gas and mixed homogeneously with it. At low fuel-flow rates, when the small right-angle nozzle was used and no air was supplied directly through the side tube, enough air was entrained at the base of the tube due to the convection currents of the hot gases from the smoke lamp to generate a small rich Bunsen flame on the tube nozzle. Under these conditions, the smoke filament was not disturbed and passed undistorted to the flame.

The four types of smoke-burning flame that could be generated by varying the fuel-and air-flow rates and the methods of injection already described are as follows:

(1) Nozzle-injected ethylene diffusion flames burning laminar smoke filaments

(2) Tube-injected ethylene diffusion flames burning homogeneously mixed smoke

(3) Nozzle-injected ethylene-entrained air rich Bunsen flames burning smoke filaments

(4) Tube-injected ethylene and air Bunsen flames burning homogeneously mixed smoke.

Direct measurements of fuel-air ratio could not be conveniently made on the Bunsen-type flames because of the indeterminate amount of air entrained at the bottom of the tube. Instead, flames of ethylene and air of known fuel-air ratio were burned on an auxiliary closed tube, and the fuel and air flows to the open tube were adjusted until the visual appearance of the test flame corresponded to the visual appearance of the known flame. Thus, it was possible to duplicate with adequate precision several lean, approximately stoichiometric, and rich flames. During the experimentation, a photographic record was made of all stable flames of interest. All photographs were taken at a magnification of two diameters.

Quantitative Measurements of Smoke Flow

The wick lamp was burned at several flame heights and the smoke formed was collected at the top of the large tube by means of a suction funnel containing a sintered glass disk and a glass-wool liner. The funnel was weighed before and after the collection to determine the amount of smoke generated by the lamp per second. The smoke issued from the tip of the smoke lamp flame in the form of a thin filament. A shadow photograph was made of each filament generated by the smoke lamp at the measured smoking rates. These photographs were used as guides in determining smoke concentrations by comparing them with the smoke filaments used in the subsequent experimentation. This comparison method was more convenient than collecting and weighing the smoke for each flame studied. The amount of smoke given off by the smoke lamp was found to lie in a measurable range from 0.01 to 0.50 milligram per second. Even less smoke than the 0.01 lower limit gave a yellow coloration to a flame, but the smoke lamp could not be adjusted precisely enough to give reproducible data below a smoke-flow rate of approximately 0.01 milligram per second. The smoke filament appeared as a faint gray thread 0.5 millimeter in diameter at a smoke-flow rate of 0.01 milligram per second. The filament retained a smooth homogeneous appearance at a smoke-flow rate from 0.01 to 0.10 milligram per second. At smoke-flow rates from 0.10 to 0.50 milligram per second, the filament became increasingly irregular and stringy in appearance. At the upper limit of smoke formation, the filament consisted of a 3.0-millimeter-diameter irregular stream of smoke strings. These small strings and clumps of agglomerated smoke will be called soot in the rest of the report.

RESULTS

Appearance of Flames Burning Smoke

Nozzle-injected ethylene diffusion flames burning laminar smoke filaments. - When smoke filaments of various concentrations were led into ethylene diffusion flames from 2 to 6 inches high, no smoke was observed leaving the tip of the diffusion flame. In addition, no sign of blackening was visible on a white porcelain dish held over the flame. The carbon burned as a yellow streak only faintly visible in the center of the ethylene-flame luminous zone. With an increase in the smoke concentration, smoke strings were formed in the filament. No difference was observed in the flame itself but discrete flecks of agglomerated smoke, or soot, could be collected on the white porcelain dish held above the flame. This type of flame could not be satisfactorily photographed because of the guttering of the flame tip, a phenomenon that occurs in diffusion flames of the size studied.

Tube-injected ethylene diffusion flames burning homogeneously mixed smoke. - Diffusion flames burning admixed smoke were indistinguishable from normal diffusion flames of hydrocarbons. All the smoke was burned in the flame at the lower smoke-flow rates, but at the higher smoke-flow rates some smoke escaped from the flame. The flame smoking from an excess of admixed smoke resembled a flame smoking independently at points above its critical smoking height. No photographic record was made of diffusion flames burning admixed smoke because of the previously mentioned lack of visible difference in the two types of flame.

Nozzle-injected ethylene-entrained air rich Bunsen flames burning smoke filaments. - Figure 2(a) shows the rich Bunsen flame generated on the nozzle when the air flow is shut off and all the air is supplied by the chimney convection due to the smoke lamp. The flow rate of ethylene in all the flames shown in this figure was 1.2 cubic centimeter per second. Parts (b), (c), and (d) of figure 2 show the appearance of the flames when burning smoke filaments whose flow rates are appreciably less than 0.01 milligram per second. With even the smallest filaments, the smoke is not completely consumed in the inner cone but extends an appreciable distance into the outer cone before it is completely burned. Parts (e), (f), (g), and (h) of figure 2 show the appearance of the flame when burning filaments of smoke within the range of 0.01 to 0.07 milligram per second. The incandescent streak of carbon extends higher into the outer cone as the smoke concentration is increased until it reaches the limits of the outer cone. Further increase in the smoke concentration causes a thin filament of smoke to escape from the tip of the incandescent streak. From this point on, continued increases in smoke concentration increase the size of this escaping smoke filament.

Tube-injected ethylene and air flames burning homogeneously mixed smoke. - Photographs of Bunsen flames taken at lean, stoichiometric, and rich fuel-air ratios are shown in figure 3. The fuel flow was 8.0 cubic centimeters per second in all cases. The smoke flow in the first vertical row of photographs is approximately 0.01 milligram per second. The approximate smoke flows in the second and third vertical rows of photographs are 0.05 and 0.10 milligram per second, respectively. The first addition of smoke to the fuel-air mixture caused the inner cone to change to a uniform yellow color. The turbulence in the flame tube caused by the air jet mixed the smoke homogeneously with the fuel and air to give this effect. (This initial phase is not shown in fig. 3, inasmuch as its photograph cannot be distinguished from a photograph of the blue inner cone of a normal Bunsen flame.) A more critical examination of the yellow flame revealed that the color of the inner cone was still visible, and that the yellow coloration seemed to lie on the outside of the inner cone in the outer mantle of the Bunsen flame. A slightly greater smoke concentration caused a faint aureole to appear around the inner cone (fig. 3(a)). With a decrease in air, this aureole increased in size, extending farther into the outer cone as an incandescent yellow haze (fig. 3(g)), but retaining its faint character. As more smoke was added to flames of each fuel-air ratio, the aureole around the inner cone brightened to the intense light yellow characteristic of hydrocarbon diffusion flames. Increasing amounts of smoke caused the bright region to extend into the outer cone until the whole outer cone was bright with incandescent carbon. No smoke was observed leaving the tips of any of these flames. The incandescent smoke extended only to the limits of the original outer cone of the flame, regardless of the fuel-air ratio of the flame. Thus, for very lean flames, the maximum amount of smoke burns in a compact aureole (fig. 3(c)), whereas the same amount of smoke in rich flames burns as a large brush flame around the inner cone (fig. 3(i)). Even those flames in which the incandescent carbon filled the whole outer mantle did not deposit smoke on a white porcelain dish held over the flame. When the smoke concentration was increased above a flow of 0.10 milligram per second, however, the flame decreased in intensity and the yellow color changed to red-orange. The homogeneous incandescence disappeared and was replaced by a series of orange streaks following the streamlines within the flame. Flecks of agglomerated smoke, or soot, could be collected on the white porcelain dish held above the flame at smoke-flow rates above 0.12 milligram per second. Lean flames tended to blow off if the smoke concentration was increased much beyond this flow rate but rich flames, although increasing in height, remained stable.

Efficiency of Smoke Combustion in Streaked Bunsen Flames Burning Admixed Smoke

Smoke measurements with the collection funnel were made with and without a Bunsen flame present on the nozzle. The measurements were made on streaked flames burning more than 0.12 milligram per second of smoke. The ratio of the weights of smoke collected with and without the flame for a stoichiometric Bunsen flame burning 8.0 cubic centimeters per second of ethylene and 0.20 milligram per second of smoke revealed that 95 percent of the smoke was burning in this flame. The smoke passing through the flame did so in the form of discrete, compact specks of soot of relatively large size.

Relative Carbon Atom Concentrations in Smoke Filament and Fuel Passing Through Inner Cone

For the smoke filament burning in the rich Bunsen flame, the smoke-flow rate is approximately 0.07 milligram per second just before smoke begins to appear at the tip of the incandescent streak (see fig. 2(h)). The total ethylene flow rate is 1.2 cubic centimeters per second. At these conditions, measurements on figure 2(h) show that the radius of the smoke filament is 1.0 millimeter and the radius of the base of the flame cone is 7.5 millimeters. Inasmuch as the ratio of the areas of circles is directly proportional to the square of the radii, the ratio of the cross-sectional areas of the smoke filament and the total gas stream is 1:56. In the 60-centimeter path of the flame tube, the fuel-air mixture should mix homogeneously with the smoke. Therefore, one-fifty sixth of the fuel per second, or 0.021 cubic centimeter of ethylene, flows through the same cross-sectional area as does 0.07 milligram of smoke. At standard conditions, 22,412 cubic centimeters of ethylene contain 24 grams of carbon, or approximately 1.0 milligram of carbon per cubic centimeter; 0.02 cubic centimeter of ethylene thus contains 0.02 milligram of carbon. The ratio of smoke carbon atoms to fuel carbon atoms within the smoke filament as it approaches the flame front is therefore 0.07:0.02, or 3.5:1.

DISCUSSION

The experimentation described in this report reveals that appreciable amounts of smoke will burn in both diffusion and Bunsen flames, as evidenced by the comparative concentrations of smoke and fuel contained within a carbon filament that can be passed into a rich Bunsen flame and burned completely. At the intercept of the smoke filament and the luminous zone, the smoke concentration in terms of the number of carbon atoms is about 3.5 times the number of carbon atoms contained in the fuel. It is open to question as to how near this ratio could be approached in a homogeneous mixture of smoke and fuel. Additional factors that might affect this ratio in some turbojet applications are gas turbulence and the rapid quenching of the hot gases by secondary air.

The extent to which agglomeration affects the complete combustion of carbon can be realized by comparing the relative smoke concentrations in Bunsen flames burning smoke filaments with those burning admixed smoke. The flame burning the admixed carbon begins to smoke when its carbon concentration is a little more than 0.4 percent of the concentration of carbon in the portion of the flame burning the smoke filament. The explanation would appear to be in the agglomeration of the smoke. The bunsen flame burning agglomerated smoke burns the major portion of the smoke entering the flame; the few percent of smoke passing through the flame do so in the form of large compact flecks of soot. Apparently, any clump of carbon nodules of a reasonable size will completely burn in a flame, but oversize clumps do not have enough time to burn completely during transit through the reaction zone.

The appearance of flames burning smoke suggests that the smoke does not burn completely in the inner cone of the flame. This is demonstrated in figure 2(c) where a minute filament of carbon with a flow rate of less than 0.01 milligram per second extends an appreciable distance into the outer cone before being completely consumed. The lean flames represented by figures 3(a), 3(b), and 3(c) have extra air in the mixture with which the carbon particles react. Because of the relatively large size of these particles in comparison to atoms or fuel molecules, a complete reaction takes an appreciable length of time and the incandescent particles drift out into the outer cone during this time. For stoichiometric and richer flames, some of the air for the combustion of the carbon must be supplied by diffusion. This fact accounts for the large brush flames of burning carbon with the richer flames. The carbon particles are heated to incandescence by the hot gases, and remain incandescent until they are reduced to gaseous products. The greater the concentration of carbon particles, the farther they must drift before reacting with sufficient oxygen by diffusion to be transformed.

SUMMARY OF RESULTS

1. Diffusion and Bunsen flames can completely burn high concentrations of smoke if the smoke particles are finely divided.

(a) Smoke can be completely burned in localized zones having a smoke-fuel carbon ratio as high as 3.5:1 in the flame, if the smoke is finely divided.

(b) Clumps of agglomerated smoke will pass through the reaction zone without completely burning even though the over-all smoke-fuel carbon ratio is low.

2. The combustion of smoke occurs in both the outer and the inner cone of a Bunsen flame.

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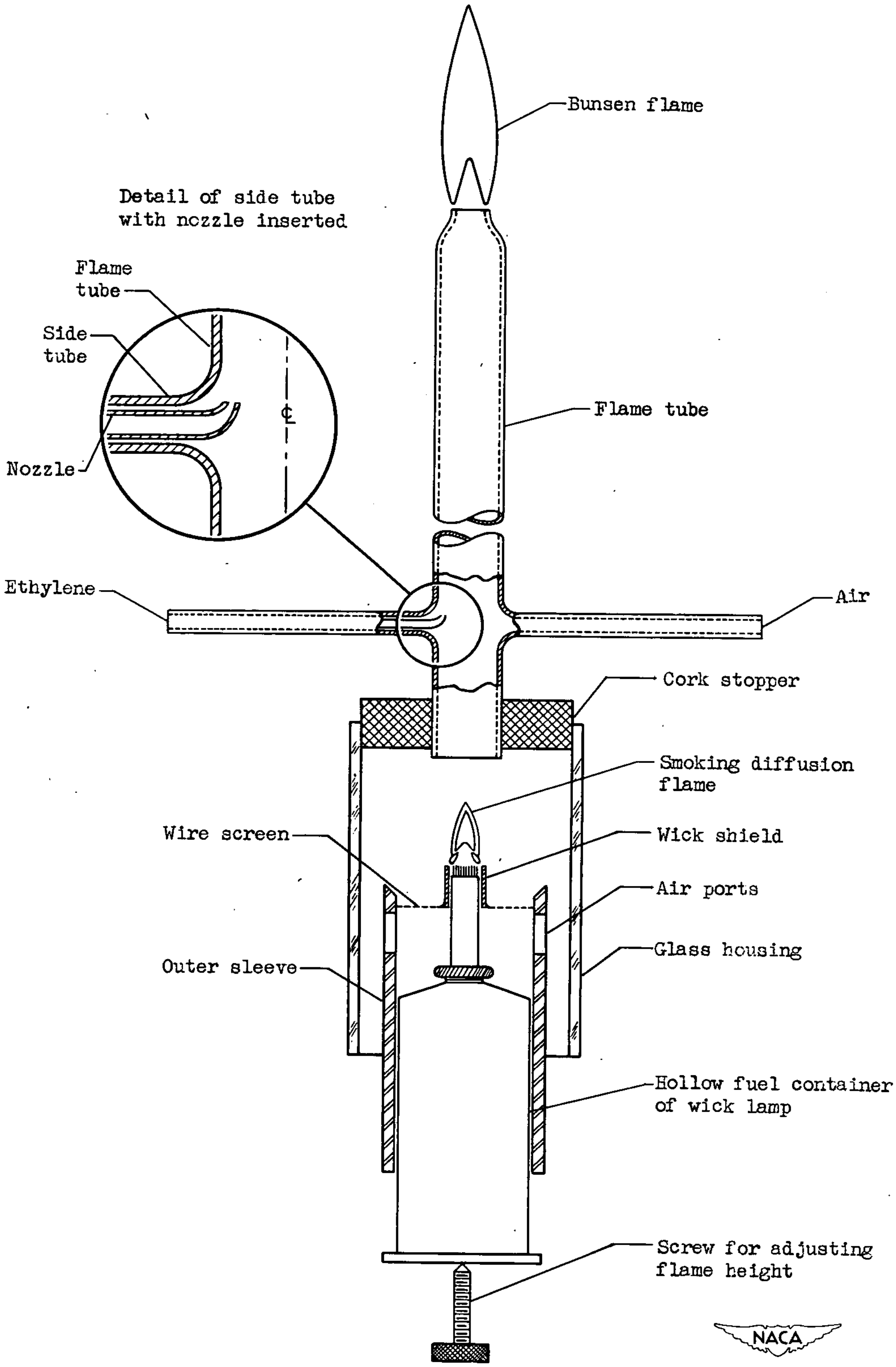

Figure 1. - Apparatus used for burning admixed smoke in flames.

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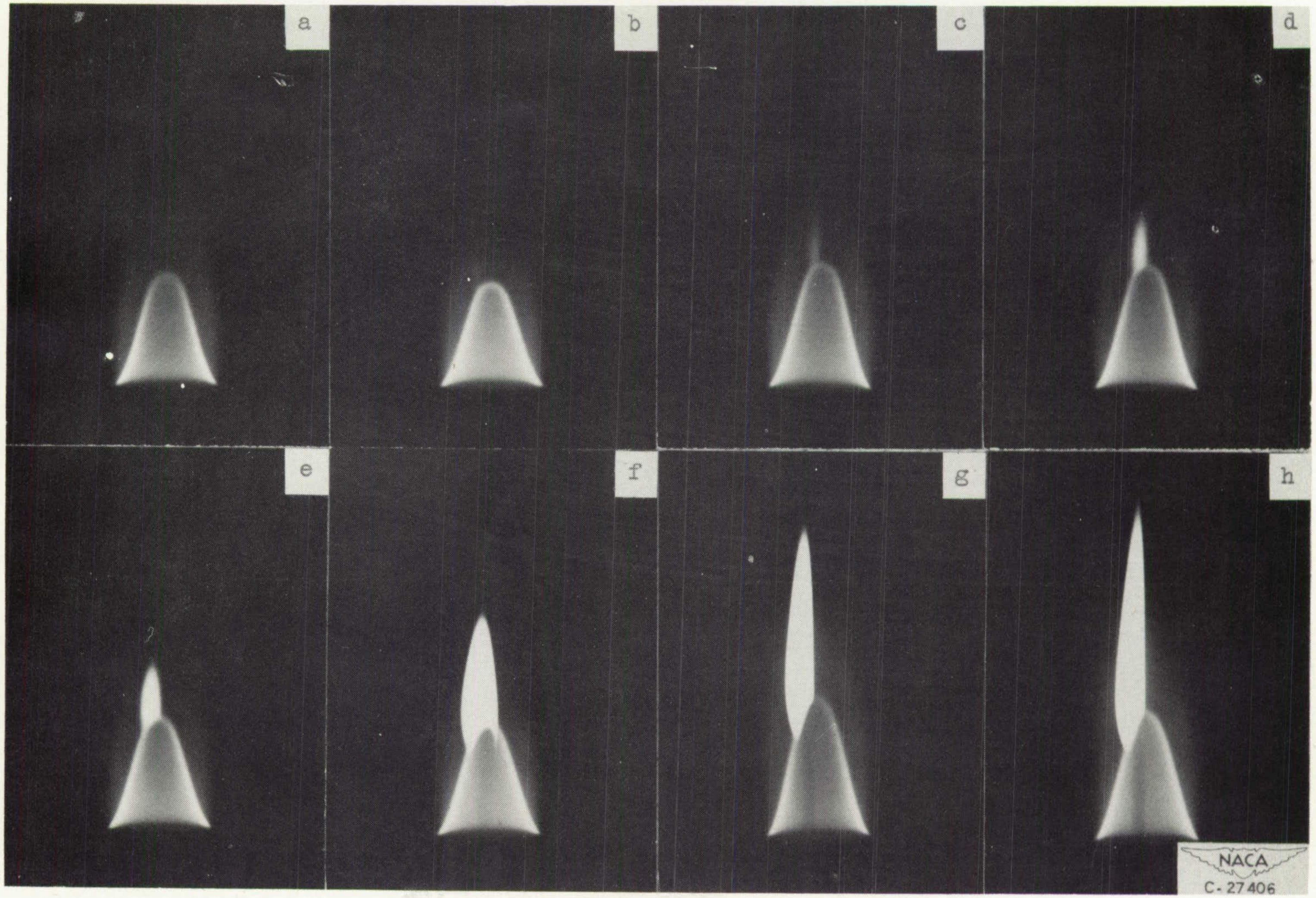

Figure 2. - Smoke filaments burning in rich ethylene Bunsen flames. Ethylene flow rate, 1.2 cubic centimeters per second; smoke flow rate, 0 to 0.07 milligram per second. 2X.

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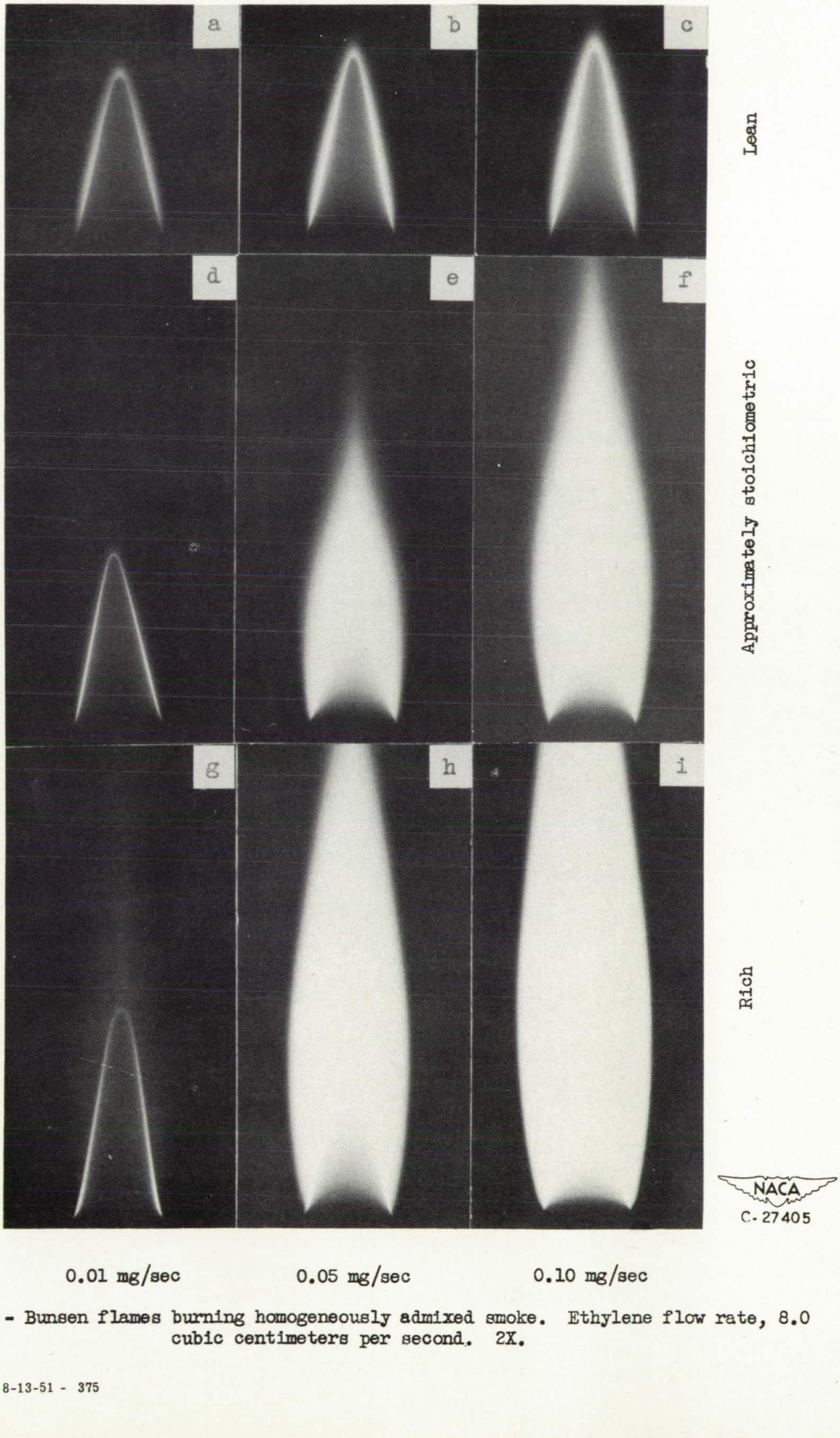

Figure 3. - Bunsen flames burning homogeneously admixed smoke. Ethylene flow rate, 8.0 cubic centimeters per second. 2X.