# Soot Formation in Ducted Turbulent Diffusion Flames

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**A vertical combustion wind tunnel was built in which confined turbulent diffusion flames were studied. Measurements were made of the mean soot volume fraction in turbulent ethylene flames using laser extinction. Velocities were measured with laser Doppler velocity, and radiation was detected with a wide-view-angle radiometer. The flames were burned under three conditions of axial pressure gradient: 0, −32, and −92 Pa/m. The accelerating flow was produced by a converging wind-tunnel working section. It was found that the latter pressure gradient caused the soot loading to fall by one-half, with a commensurate fall in the radiation emitted by the flame. The flame was shorter when it was accelerated. Turbulence intensities were also greater in the convergent duct. The results indicate the potential impact of pressure gradients on the relatively slow chemistry of soot formation.**

## Introduction

ISOTHERMAL free shear layers such as turbulent jets have been studied for many years. More recently, the chemically reacting turbulent shear layer has been the object of considerable attention. In almost all of the studies of both types of flows there were no mean pressure gradients. An axial pressure gradient may be imposed on a free shear layer if it is confined in a sufficiently large duct through which an external or outer flow is maintained. The duct may be either convergent or divergent. In the former case a favorable gradient is established and the outer flow accelerates; in the latter case the unfavorable pressure gradient slows the outer flow.

Normally one would expect that a favorable pressure gradient would tend to suppress turbulence in an isothermal flow. This is the concept behind the use of contractions on wind tunnels. However, if combustion is occurring in the flow and there are significant density variations, then the response of the shear layer to the imposed mean pressure gradient may be different. In one of the few studies to look into this matter, Starner and Bilger[1] performed measurements of the velocity field in a hydrogen air diffusion flame that burned in a wind tunnel. They made the interesting observation that the flame became shorter when either a favorable or unfavorable pressure gradient was imposed on the flow. Measurements of the velocities indicated that the favorable pressure gradient caused the turbulence intensities to be enhanced. The effect was ascribed to a pressure-velocity correlation in the equation for turbulent kinetic energy.

The experiment suffered from some flaws. The wind tunnel was horizontal, and, as a result, buoyancy forces tended to cause a circulation in the flow. In addition, the working section walls were adjusted in only one direction so that symmetry was not maintained. Consequently, the flames assumed an elliptical shape that gave rise to some difficulty in interpreting the experimental data. Nevertheless, the results from this experiment indicated that the confinement of a turbulent hydrocarbon flame in a convergent duct may have some impact on the slower chemistry in these systems.

Among the chemical reactions in a hydrocarbon-air flame, those that lead to soot particles are probably the slowest. This has been demonstrated by Kennedy[2] in a series of experiments in a laminar stagnation-point diffusion flame. The rate of mixing between air and fuel in these flames is determined by a velocity gradient that is imposed by the flowfield. High velocity gradients lead to high rates of diffusive mixing of reactants, and if these rates are sufficiently great, then the formation of soot can be suppressed. A similar effect is evident in turbulent diffusion flames, where the mixing is achieved by turbulence.[3] High turbulence intensities can diminish the soot loading and soot radiation in these flows. Such conditions can be obtained by using high nozzle velocities for the fuel stream.[4] The flame near the nozzle is mostly blue and becomes yellow farther downstream. An additional mechanism for achieving and maintaining high turbulent mixing rates is to impose favorable axial pressure gradients on the flow. The shape of a gas turbine combustor can, for example, result in strong pressure gradients that enhance the turbulence.[5] The impact of these pressure gradients on soot formation and soot oxidation in a ducted turbulent diffusion flame is the object of our investigation.

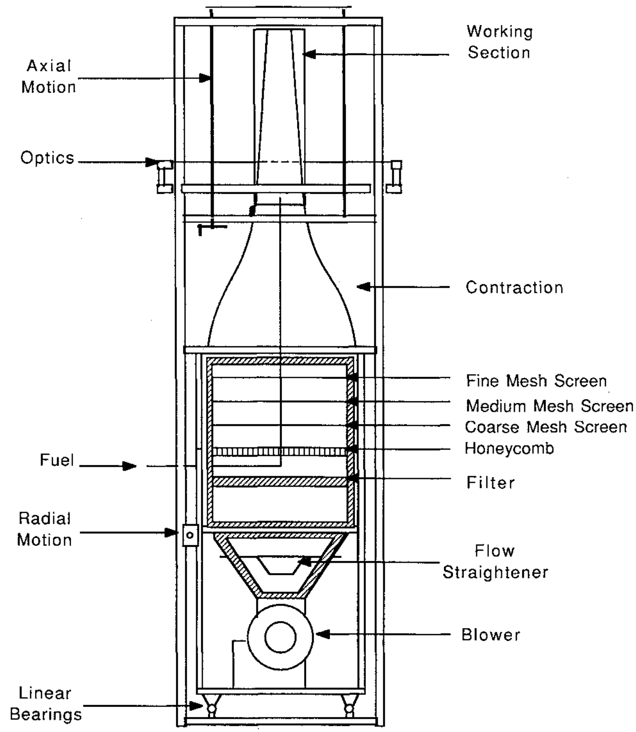


**Fig. 1 Combustion wind tunnel.**

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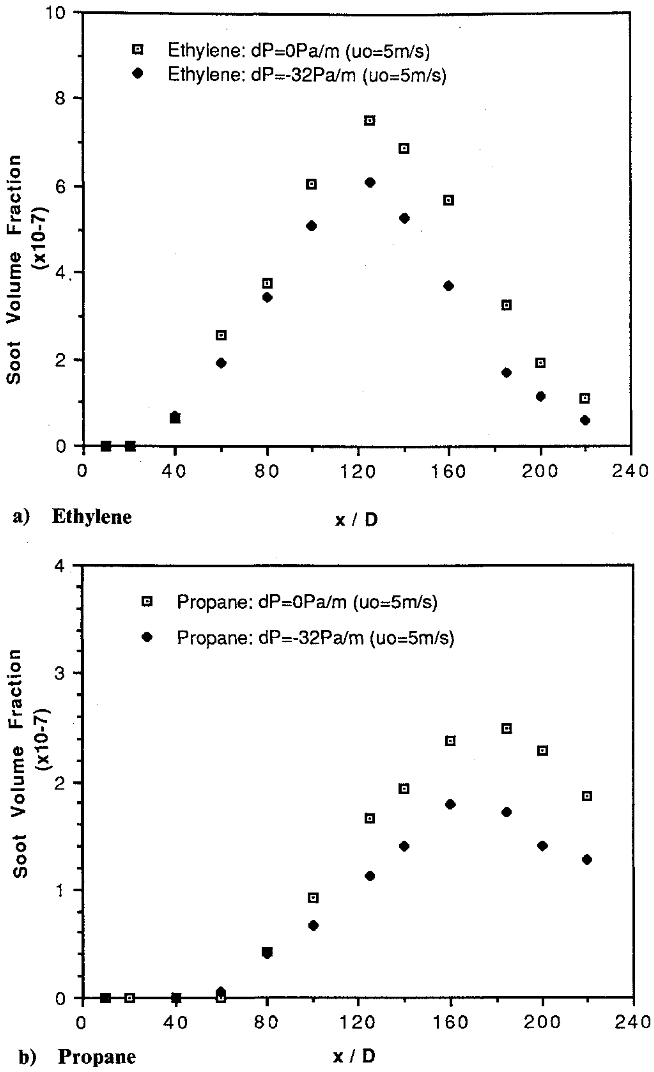


**Fig. 2 Measurements of mean soot volume fractions averaged across the flame diameter for pressure gradients of 0 and −32 Pa/m.**

## Experiment

A wind tunnel was built in which various sooting hydrocarbon fuels can be burnt as turbulent jet diffusion flames. A schematic representation of the experimental apparatus is shown in Fig. 1. The tunnel is a conventional design and provides air in the working section with a very low turbulence intensity (less than 0.5% rms of the mean velocity) at velocities between 5 and 8.5 m/s. Fuel issues from a 5-mm-diam tube that is centered in the working section. The working section is 305 × 305 mm square at its base and is 1.5 m long. An annular hydrogen flame serves to stabilize the hydrocarbon flame. The working section walls with glass windows are hinged and can be moved in and out. The other two walls are cut from a flexible metal sheet to fit the glass walls so that approximately square cross sections in the duct are maintained for the different conditions that have been studied. Minor adjustments in the shape of the flexible walls permit constant axial pressure gradients to be established without a significant loss of flow symmetry. The vertical orientation of the tunnel eliminates the effect of buoyancy in distorting the flowfield. In order to obtain axial profiles, the optics were mounted on a frame that could be cranked up and down; radial profiles were obtained by traversing the tunnel horizontally through the laser beam.

Two fuels were used: $C_2H_4$ and $C_3H_8$. The Reynolds numbers for these flames were 23,000 and 31,600, respectively. Three axial pressure gradients were investigated: 0, −32, and −92 Pa/m. Measurements of an average soot volume fraction were obtained by observing the extinction of an argon laser with a photodiode. Line-of-sight measurements were inverted with an "onion-peeling" technique to provide radially resolved profiles.

Velocities were measured with a one-component laser Doppler velocity (LDV) system. The flame was seeded with alumina particles that had a normal diameter of 1 $\mu$. Successful seeding of both flows simultaneously could not be achieved. Hence, the results presented here represent turbulent zone quantities. A correction for velocity bias was not applied.

## Results

Measurements of the average soot volume fraction with a zero axial pressure gradient are shown in Fig. 2 along the cen-

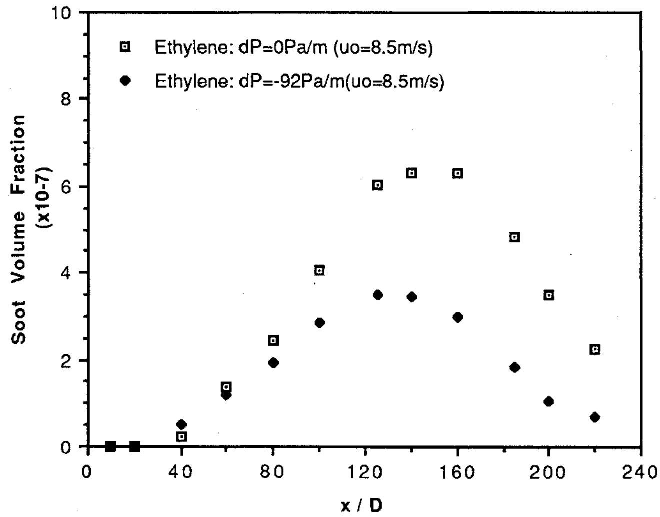


**Fig. 3 Measurements of mean soot volume fraction averaged across the flame diameter for pressure gradients of 0 and −92 Pa/m with ethylene.**

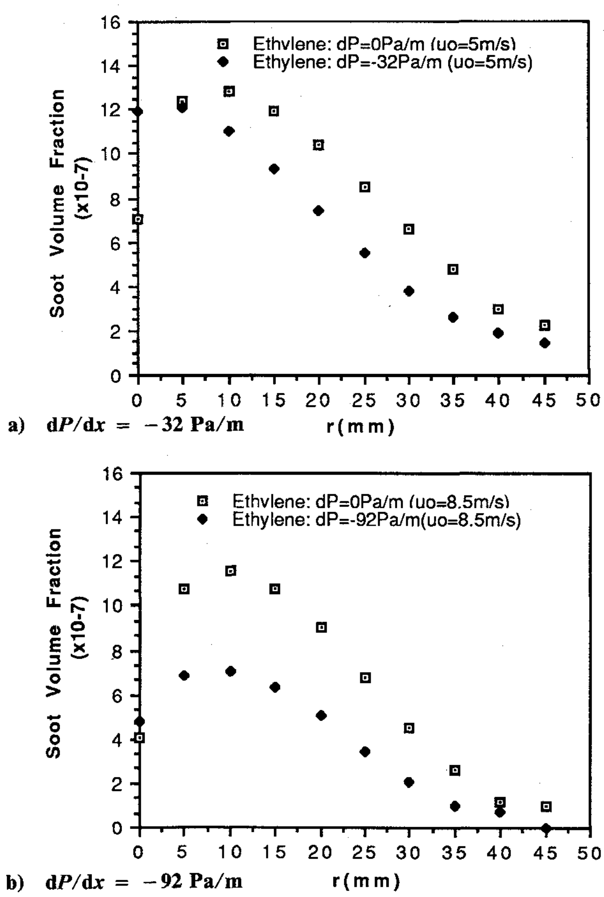


**Fig. 4 Radial profiles of mean soot volume fractions in an ethylene flame at $x/D$ = 125.**

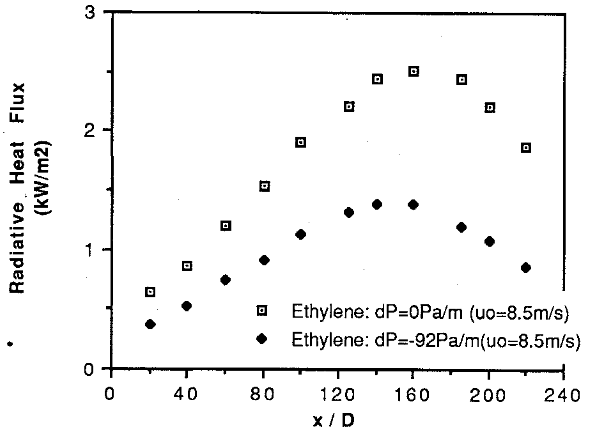


Fig. 5 Radiative heat flux for ethylene flames.

terline of the flame; the freestream velocity was 5 $ms^{-1}$ at the exit of the tunnel contraction. These line-of-sight measurements give a relative measure of the amount of soot in each flame. It can be seen that propane produces much less soot than ethylene. Similar results obtained with a pressure gradient of $-32$ Pa/m are also shown in Fig. 2. This modest pressure gradient was obtained by decreasing the cross-sectional area of the working section from 93,000 $mm^2$ at the bottom to 52,200 $mm^2$ at the top. A measurable effect on the maximum soot loading is apparent for this flame with typical decreases of about a factor of 25%. It should be noted that the physical appearance of the flame was altered by the increase in the pressure gradient; i.e., the flame shortened by about 300 mm. This effect is evidence of the increase in the turbulence intensity and the rate of mixing in the flame.

Figure 3 presents results in the ethylene flame that were obtained with pressure gradients of 0 and $-92$ Pa/m; these conditions were achieved by operating the tunnel with the same area decrease as that reported earlier but at a freestream velocity of 8.5 $ms^{-1}$. As a result of the higher freestream velocity, the flame is longer compared to the flame with a freestream velocity of 5 $ms^{-1}$. The laser extinction measurements show that the decreasing trend in the soot loading continues with further increases in the axial pressure gradient.

Radial profiles of the soot volume fraction in the ethylene flame at 125 nozzle diameters downstream are presented in Fig. 4 for a zero pressure gradient and for pressure gradients of $-32$ and $-92$ Pa/m. The distribution of soot in the flame is similar under all conditions, but again the soot loading is decreased each time the pressure gradient is increased. (Values on the centerline suffer from uncertainties related to the onion-peeling technique.)

Radiation heat fluxes were measured at a position 0.3 m from the flame with a thermopile radiometer that has a 150-deg view angle. Measurements of the radiative heat flux are shown in Fig. 5. The effect of increased pressure gradients on radiation is apparent. A factor of about two decrease in the peak radiation flux results from the imposition of a $-92$-Pa/m pressure gradient on the flame. This result is consistent with an optically thin model for the sooty flame and the previously reported drop in soot loadings. Under these conditions the radiation should be linearly proportional to the soot volume fraction and the radiation flux should follow the trends in soot volume fraction if soot dominates the radiative transfer process.

The impact of a pressure gradient on the velocity field is seen in Figs. 6 and 7, which show the mean axial velocity component and its turbulence intensity, respectively. In the latter case the data have been normalized by the excess mean velocity, which is the difference between the centerline mean velocity and the velocity of the freestream flow. This is the appropriate normalization for shear-driven flows such as this jet flame. Favorable axial pressure gradients are seen to accelerate the flow in Fig. 6, where a linear increase in the freestream velocity with downstream position is apparent. For a constant-density flow this may result in the relaminarization of a turbulent flow. However, in a flame the result is an enhancement of the turbulence levels that are presented in Fig. 7. A comparatively modest axial pressure gradient can apparently have an effect on turbulence levels. This impact may be expected to translate into higher mean scalar dissipation rates, which can tend to suppress the formation of soot particles.[2]

## Discussion

A turbulent hydrocarbon diffusion flame will usually exhibit a region near the base of the flame where there is little or no yellow luminosity, which is indicative of the presence of soot. The extent of this region will depend on the sooting tendency of the fuel and on the exit velocity of the flow. An increase in exit velocities will tend to shift the onset of soot formation downstream from the nozzle. The formation of soot is due to the slowest chemical kinetics that take place in a flame. As a result, they are the first to be affected by the high rate of mixing of reactants near the nozzle. Farther downstream in a turbulent jet diffusion flame mixing rates are lower and the rate of soot formation will be controlled by the turbulent mixing.

Many years ago Tsuji and Yamaoka[6] reported the observation in a counterflow laminar diffusion flame that at a critical velocity gradient the production of soot in their flame was suppressed. This flow condition was far from the velocity gradient that was necessary to extinguish the flame itself. This phenomenon was examined in further detail by Kennedy,[2] who showed that the suppression of soot formation could be related to a critical scalar dissipation rate in a turbulent diffusion flame. The mean scalar dissipation rate should increase as the turbulence intensity increases; thus, one can expect a loca-

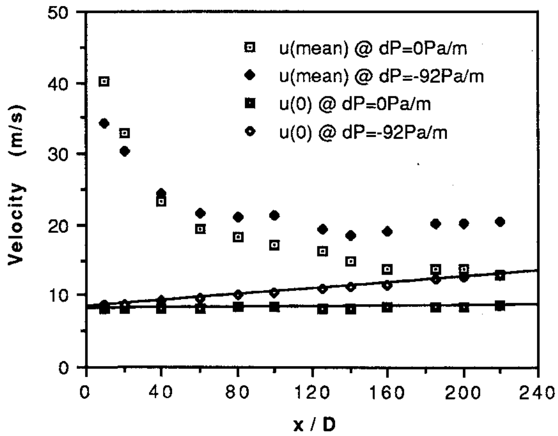


Fig. 6 Mean axial velocities $U$ (mean) along an ethylene flame centerline, freestream axial velocities $U$ (O).

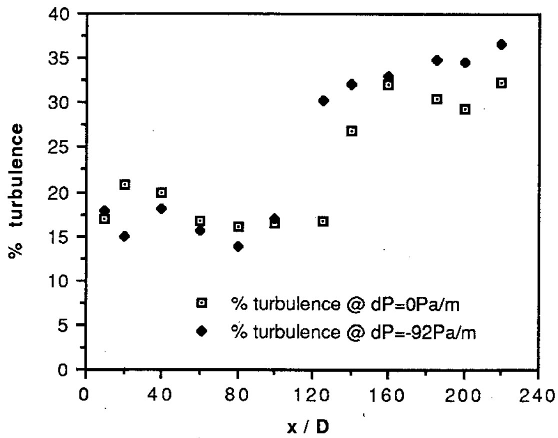


Fig. 7 Turbulence intensities along an ethylene flame centerline.

lized effect of the axial pressure gradient on the inception of soot particles.

In addition to particle inception, soot in a flame is formed from surface growth reactions; most of the soot volume fraction is a result of this mechanism. The total amount of soot that is formed depends on a number of different factors. One of these factors is the total amount of time available for surface growth. A reduction in the global residence time in the flame may lead to a reduction in the total amount of soot that is formed. An appropriate measure of the residence time for soot growth is the flame length divided by a characteristic velocity. Figure 6 shows that the velocities in the flame with the favorable pressure gradient are significantly higher than those in the flame without a pressure gradient. The reduction in the soot loading that has been observed with the imposition of an axial pressure gradient may be explained to some extent by the combined effects of the higher velocities and the shorter flame length; reduced time for soot growth leads to a lower soot loading.

A further impact on the mean soot loading in these flames is due to the rate of oxidation or soot burnout. The turbulence intensities that are shown in Fig. 7 indicate that mixing rates are enhanced in the downstream part of the flame that has an imposed pressure gradient. This indicates that a mixing-controlled oxidation rate may be augmented with a favorable pressure gradient.

Kent and Bastin[4] studied turbulent acetylene jet diffusion flames in which they discerned two regimes of soot formation and oxidation that were controlled by either mixing or kinetics. They correlated formation and burnout rates in terms of a flame residence time defined as $D/U_e$, where $D$ is the nozzle diameter and $U_e$ the jet exit velocity. However, a characteristic time of $L/U$, where $L$ is the flame length, is more appropriate in this case. The characteristic velocity $U$ would be an average velocity for the entire flame, not the jet exit velocity. As noted earlier, the flame length $L$ decreases and $U$ increases when a pressure gradient is applied; hence, the time $L/U$ is reduced and mixing rates are increased. An analysis similar to that of Kent and Bastin may help to determine whether the pressure gradient affects the soot concentration via mixing or kinetics. Unfortunately, we are not able to achieve a wide range of conditions (residence times) by adjusting the pressure gradient.

At present it is not possible to determine directly which effect (the local particle inception rate or the global residence time) is dominant in serving to determine the reduction in soot formation in flames with axial pressure gradients. Current laser diagnostic techniques are not capable of yielding spatially resolved measurements of soot volume fraction and particle number density in turbulent flames. The number density information would help to resolve the question regarding the relative importance of the particle formation and residence time mechanisms.

The significant reduction in soot loading that we have measured with a modest axial pressure gradient suggests that the successful modelling of soot formation and its radiation in combustors will need to account for this phenomenon. A contraction in the combustion chamber walls may not even be necessary if the duct is small compared to the flame thickness. The expansion of the flame may serve to induce axial pressure gradients in a chamber.

## Conclusions

A unique experimental facility has been constructed for the study of sooting turbulent diffusion flames with adjustable axial pressure gradients. Comparatively modest pressure gradients (i.e., less than one might encounter in an engine combustor) have been found to have a significant effect on the soot loading in these flames. Higher pressure gradients lead to less soot and, by inference, less radiation. One potential cause is the suppression of soot particle inception by locally high mixing rates of reactants. Another explanation is the reduction in the residence time available for soot surface growth reactions to take place and enhanced oxidation rates.

## Acknowledgment

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