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SCHLIEREN MEASUREMENTS OF FINE SCALE MIXING

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The present paper considers Schlieren measurements of fine scale mixing in a similar system as used by Mc Kelvey et al. [1]. A unique experiment using the Toepler-Schlieren apparatus was performed so to obtain quantitative mixing data for the mixing of individual air jets with helium jets.

1. Introduction

In chemical reacting systems the nature of the flow plays an important role in the mass transport of material and the resulting chemical kinetics. For example, the degree of conversion of a very fast chemical reaction is completely controlled by mixing and conversely, for very slow chemical reaction, kinetics is controlling. For the intermediate case, however, both mixing and kinetics are important parameters in predicting the degree of conversion of the reactions.

An investigation of turbulence and mixing has been reported by McKelvey et al. [1]. They reported procedure for analysis of the turbulence structure and confirmed empirical relationships by applying phenomenological concepts based upon the statistical theory of turbulence. The present paper will consider Schlieren measurements of fine scale mixing in a similar system as used by McKelvey et al. Schlieren techniques have been used extensively for qualitative examination although special techniques will permit quantitative results to be obtained [2, 3]. In our work, a unique experiment using the Toepler-Schlieren apparatus was performed so as to obtain quantitative mixing data for the mixing of individual air jets with helium jets.

2. Experimental procedure

Two different geometries of parallel multitube ejectors (A and B of Fig. 1) were used to investigate turbulence nad mixing of binary gases. The design of the ejectors was based on the work of Toor and his co-workers [4, 5, 6]. A view of the ejector nozzles (discharge ends) is shown in Fig. 2. The parallel multitube ejectors were placed in a flow module (Fig. 3) which permitted two gases with no pre-mixing to discharge into a tubular section. Hot wires were used to measure turbulence parameters, u', v', w', (rms values) and mean velocity, $\bar{U}$. Details of the turbulence measurements, analyses, and statistical reduction are reported by McKelvey et al. [1].

The flow device (Fig. 3) was designed to prevent pre-mixing of the gases. A gas enters the side chamber, strikes a baffle plate and passes through a perforated cylinder to improve the flow distribution at the entrance to the 2.5 inches long tube. Similarly, the second gas enters the forward chamber, also strikes a baffle plate, passes through a porous metal disk and through a packed bed of 4 mm glass beads located at the entrance to the 4.5 inches long tube. Each chamber was instrumented with pressure tapes and thermocouples. Attached to the discharge end of the flow device was the tubular section in which the mixing of two different gases occurred and measurements of turbulence were made.

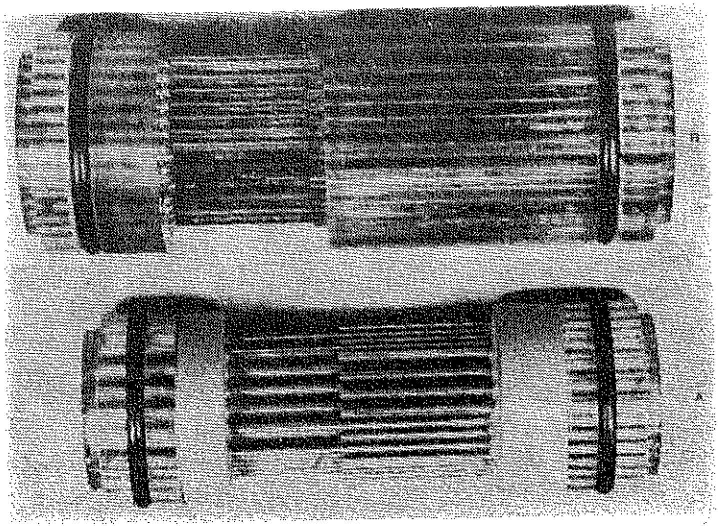

FIG. 1. Ejectors *A* and *B*.

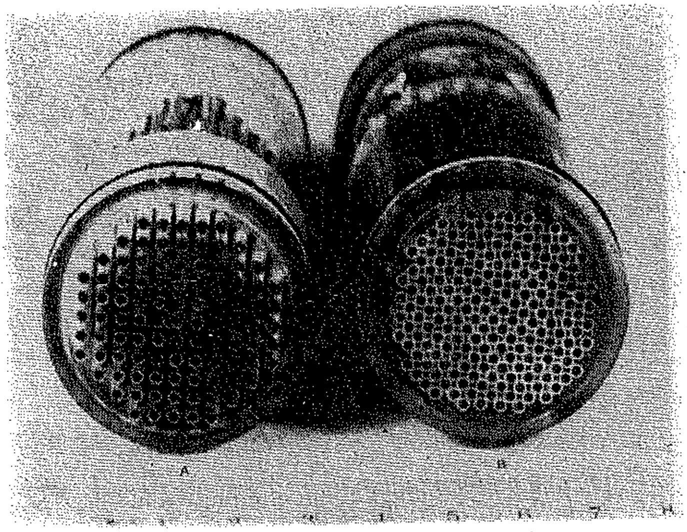

FIG. 2. Ejectors *A* and *B*. Nozzle discharge view.

Air and helium are colorless, transparent and non-illuminating gases; therefore, standard photographic techniques cannot be used to investigate gas mixing and turbulent interaction situations. Schlieren and moire optical techniques using still photography and high speed motion pictures were employed. The Toepler-Schlieren method [2, 3, 7, 8, 9, 10, 11] which has been highly successful in aerodynamic research to investigate high speed flow, heat transfer, shocks, etc., was used in this inwestigation. Fig. 4 shows the critical components of the optical system employed: 1) General Electric, GEI-32303-A Schlieren light sources capable of producing a continuous light source or triggering a light source of 6 to 9 microseconds duration, 2) Two 8-inch parabolic mirrors, 3) Knife edge, 4) Polaroid camera, viewing glass, or Fastax camera, 5) Diffraction grating — 200 lines per

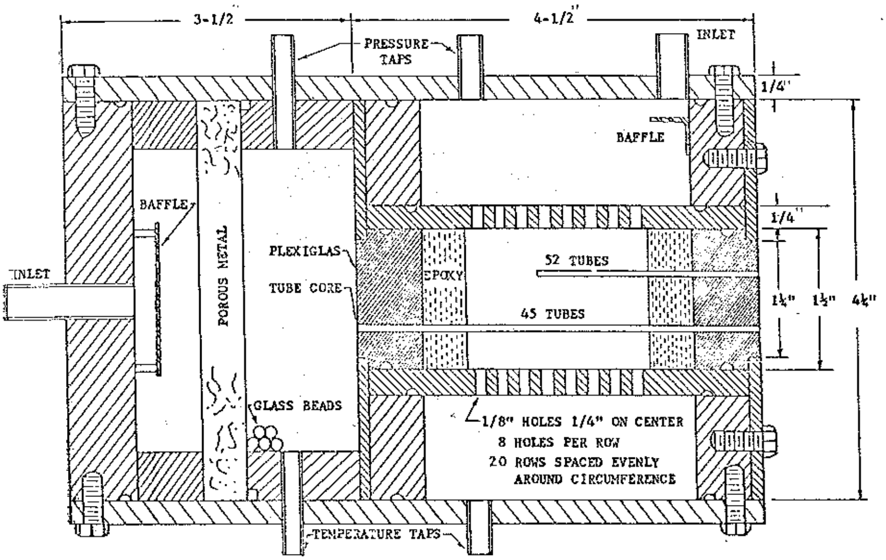

Fig. 3. Schematic of flow device for multitube ejectors.

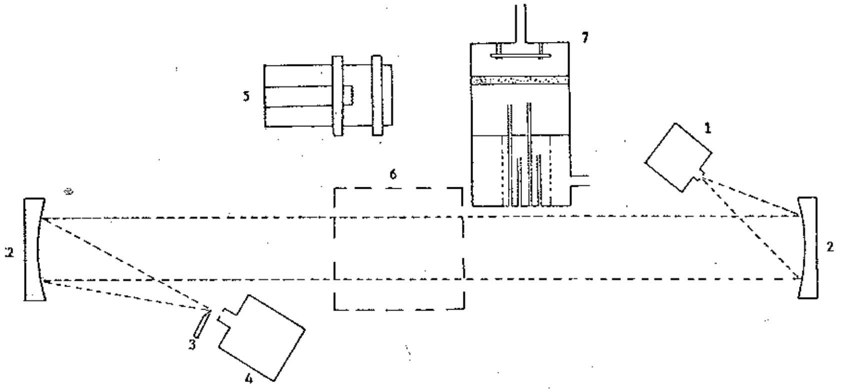

Fig. 4. Schematic of Schlieren apparatus.

inch, 6) Location of diffraction gratings when taking moiré patterns, and 7) Test model.

Since the Schlieren technique depends on the refractive difference between the fluids being studied and the ambient, the channel box shown in Fig. 5a was constructed. The box is designed such that the ejecting gases (air-helium) flow through a center channel and then the gases turn flowing counter current in an outer channel (Fig. 5b). By the time the flow returns, the mixing is assumed complete. Experiments showed no mixing between the gases flowing in the inner chamber and the mixed gases flowing counter current in the outer chamber. The idea was to eject the air-helium flow into an environment that is the final mixed composition of the air-helium mixing. As the air jets mix with the helium jets some distance from the nozzles, the refractive index would change axially and eventually equal that of the final mixed composition. The axial distance where the refractive index of the individual air and helium jet mixing is equal to the mixed air-helium environment is considered the mixing length.

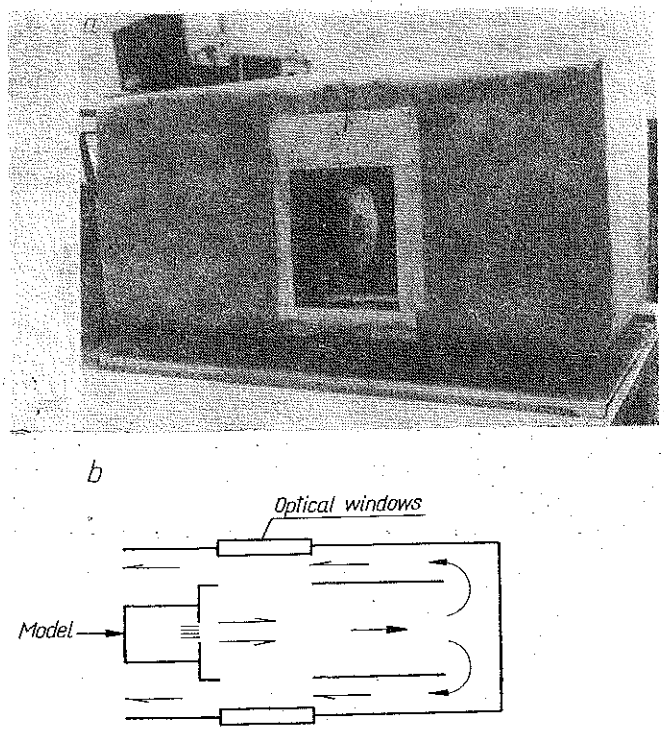

FIG. 5. Channel flow box; a) channel flow box assembled about the flow model; b) Schematic of flow passages in channel flow box.

High speed motion picture (Wollensak 16 mm Fastax camera) were taken of air-helium flow with and without the box (Fig. 5) and with Schlieren or moiré optics (substitute two 4×4 inch gratings for the knife edge). The camera was positioned behind the knife edge and replaced the polaroid camera (Fig. 4), and had a potential maximum speed of 7000 frames per second. Individual frames were analyzed with both a Joyce Loebl and a Mann-Data microdensitometer to obtain scalar air-helium mixing data.

3. OPTICAL ANALYSIS

A typical schlieren photograph is shown in Fig. 6a for air-helium mixing without the channel flow box. It represents the entire plume of air and helium ejecting from the multitube ejectors. This type of photograph shows the mixing of the jet fluids with the ambient environment, and only limited information can be obtained about the mixing of the individual jets. It also shows turbulent characteristics, but yields little information on its structure. Schlieren photographs of the type shown in Fig. 6a have been reported extensively in the literature and are typical of single jet experiments where there is either subsonic or supersonic flows.

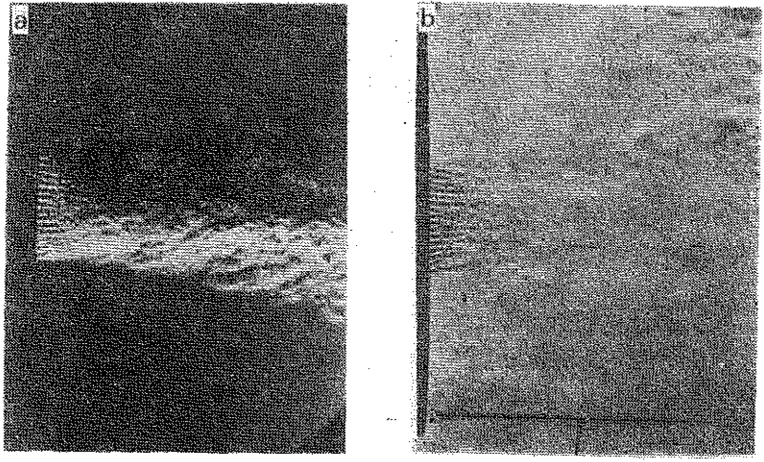

FIG. 6. Air-helium mixing made visible by Schlieren method; a) without channel box, b) with channel box.

The channel flow box (Fig. 5) was designed so that quantitative information of two or more fluids mixing could be obtained. Figure 6b in contrast to Fig. 6a shows the mixing of air jets with helium jets in the axial direction. Semi-quantitative information of air mixing with helium was obtained using the channel flow box by taking high speed motion picture of the flow and analyzing these negatives with the microdensitometer.

Figure 7 is one example of 140 typical plots obtained with the Joyce Loebl microdensitometer. (note: The Mann-Data Micro-Analyzer products similar plots) from schlieren high speed motion picture negatives taken with the channel box. This figure is a plot of optical density as a function of radial position obtained by a diametric traverse perpendicular to the jet flow at one axial position. The mixing region identifies the relative width of jets of air and helium. Similar recordings were obtained for 20 successive frames (film speed $\approx$6500 frames per second) and at seven axial distances.

These data were statistically reduced to obtain the relative transmittance which is plotted in Fig. 8 (maximum, minimum and average of five values). Figure 9 shows a plot of relative turbulence intensity, $u'/\bar{U}$ for ejector B at the same Reynolds number that the optical studies were made. There is an experimental difference, however, since the relative turbulence intensity were measurements of air in both sets of jets ejecting into the tubular section. Nevertheless, one can see the similarity of the relative transmittance intensity (Fig. 8) and relative turbulence intensity (Fig. 9).

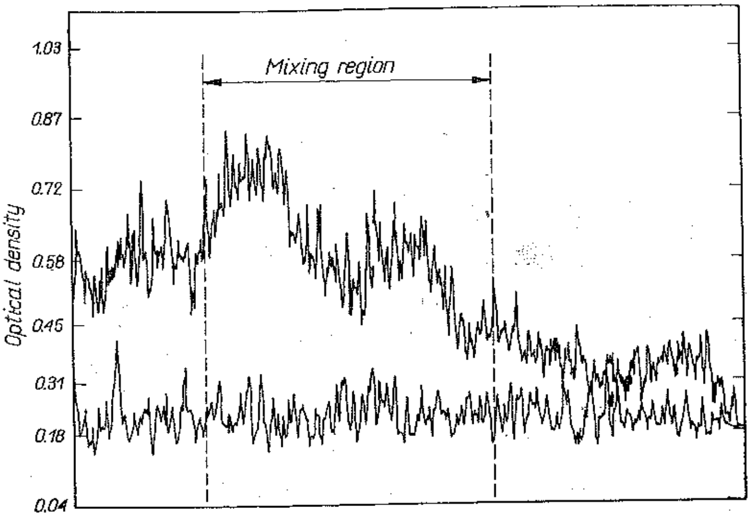

FIG. 7. Optical density variation across the jets.

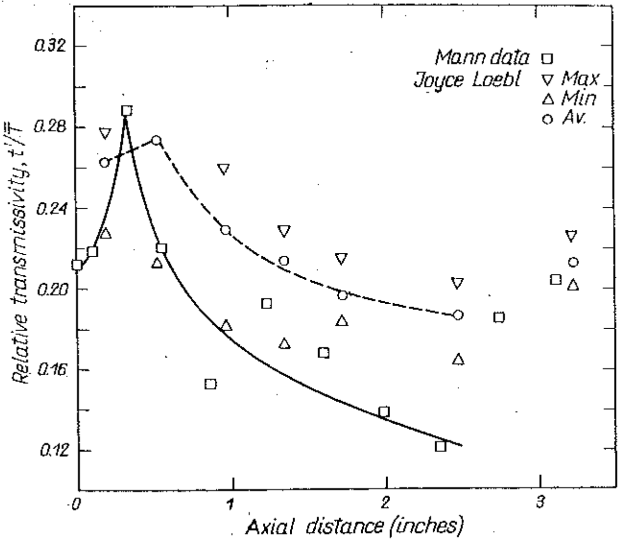

FIG. 8. Microdensitometer data for ejector *B*.

The microdensitometer measure optical density and the transmittance was computed by

$$\text{Transmittance} = \frac{1}{\text{Antilog Optical Density}}. \tag{3.1}$$

The intensity of transmittance (t'_{trans}) was computed statistically from transmittance data by calculating

$$t'_{\text{trans}} = \sqrt{\frac{\Sigma(T_{\text{trans}} - \bar{T}_{\text{trans}})^2}{n}}, \tag{3.2}$$

where n is the number of samples. The relative transmittance intensity ratio is defined as

$$\frac{t'_{\text{trans}}}{\bar{T}_{\text{trans}}} = \frac{\sqrt{\frac{\Sigma(T_{\text{trans}} - \bar{T}_{\text{trans}})^2}{n}}}{\bar{T}_{\text{trans}}}. \tag{3.3}$$

The values at an axial distance of 3.25 inches (Fig. 8) is attributed to a large globe of air and helium in the counter current flow of mixed air-helium. The globe was identified during careful examination of the negative and is the reason for the increase in relative transmittance at this point.

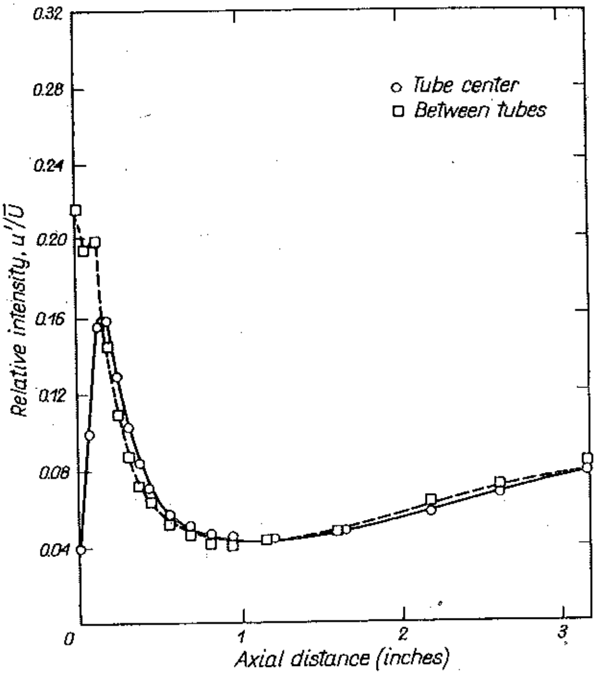

FIG. 9. Ejector B relative intensity at $N_{\text{Re}} \approx 2600$.

The transmittance data obtained with this ejector geometry is complex since, optically, the film records an integrated signal of the light being diffracted by all the jets nad the counter flowing environment. The optical experiments originally were not designed for quantitative evaluation but rather for qualitative study. However, with the availability of the microdensitometers, the successful attempt to quantify mixing information indicates that the channel box experiment can be a useful quantitative procedure in applying schlieren techniques to turbulence mixing research.

Fast Fourier trasnforms were made of the optical data to convert the information from a space domain into a spatial frequency domain. This suggests searching for frequency components associated with continuous wave forms. Figure 10 is a power spectrum of the relative amplitude at two axial positions. This figure indicates the change in eddy size as the total jet interaction passes from a region close to the nozzles to a region further away. For comparison, the background noise level is included.

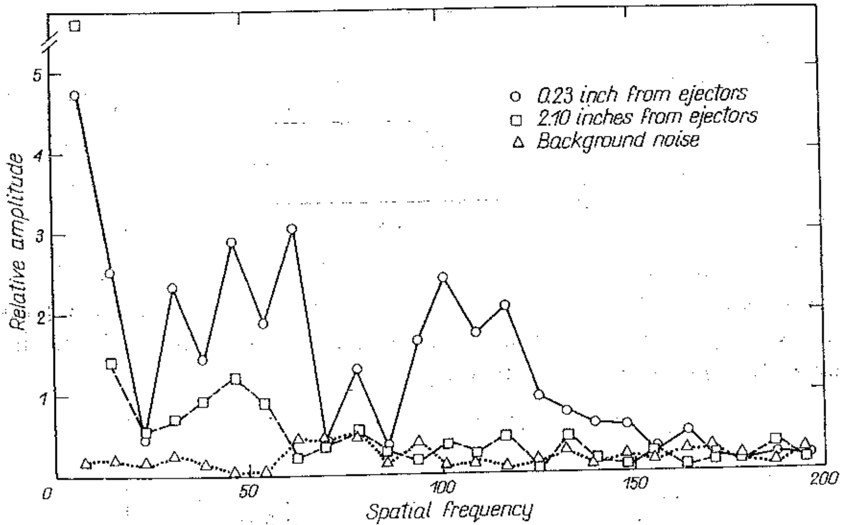

FIG. 10. Fast Fourier transform — power spectrum.

4. CONCLUSION

A unique optical experiment was developed expanding the capabilities of the Toepler-Schlieren technique to investigate mixing of binary gases. The new procedure can be extended to studying other types of turbulent flowing systems. By means of a channel flow box, unmixed gases (air-helium) were ejected into an environment representing their final mixture. High speed movies photographed the air mixing with helium. The negatives were examined with a microdensitometer and optical density was converted by statistical analysis to relative transmittance intensity. The results gave semi-quantitative information of the air-helium mixing lengths. The analysis is limited since,

1) the ejector design has a three-dimensional flow field, which at best the Schlieren method gives two-dimensional results

2) no standard (i.e., optical density) was exposed on the film to quantitize the results.

3) the developing procedure of the film was not optimized for the experiments, i.e., the effect of residual silver is unknown and thought to be of the same magnitude as the spot size examined with the microdensitometer.

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The work is based on the Ph.D. thesis by one of us (S. ZAKANYCZ).

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STRESZCZENIE

POMIARY DOSKONAŁEGO MIESZANIA GAZÓW NA APARATURZE SCHLIERENA

W niniejszej pracy przedstawiono pomiary doskonałego mieszania gazów na aparacie Schlierena w podobnym układzie dyn jaki rozważali MCKELVEY i in. [1]. Przeprowadzono oryginalne doświadczenie wykorzystując aparaturę Toeplera-Schlierena celem otrzymania ilościowych danych dotyczących mieszania pojedyńczych strumieni powietrza ze strumieniami helu.

Резюме

ИЗМЕРЕНИЯ ИДЕАЛЬНОГО СМЕШИВАНИЯ ГАЗОВ В АППАРАТУРЕ ШЛИРЕНА

В настоящей работе представлены измерения идеального смешивания газов в аппарате Шлирена с аналогичной системой сопел какую рассматривали Мак Кельвери и другие [1]. Проведены оригинальные эксперименты, используя аппаратуру Теплера-Шлирена с целью получения количественных данных, касающихся смешивания единичных потоков воздуха с потоками гелия.

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