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VELOCITY MEASUREMENTS IN A TWO-PHASE TURBULENT JET

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Abstract—The motion of oil droplets in a round turbulent air jet is investigated experimentally. Direct information on the droplets' average velocity is obtained by means of a Laser Doppler velocimeter. Average velocity profiles of the droplets are measured along the axis of the jet and transverse to it. The results are compared to the free jet expansion.

The jet Reynolds number is in the range 10^4–10^5, the droplets' diameters are 50 μm and below and the volume concentration of the oil in the air is 10^{-6}.

At the jet exit, the air velocity is higher than the droplets' velocity, at the developed region of the jet the droplets' velocity is found to be higher than the free air jet velocity at the same location. In the radial direction, the velocity profiles of the droplets are self similar and the droplets' velocity is lower than the free air jet velocity at the same location. The droplets' velocity decay along the axis of the jet is slower than the air velocity in the free jet and the two-phase jet is narrower than the submerged free air jet at the same exit velocity.

1. INTRODUCTION

The applications of this research are numerous and the published information is voluminous. In spite of the considerable effort, there is no basic understanding of the underlying phenomena, in particular the interaction between the turbulence of the mainstream and the suspended particles (Hinze 1972). This is not surprising in view of the extreme complexity of the phenomena.

The aim of this work is to study a suspension in a relatively simple and well known flow field. To avoid the additional complexities associated with walls of conduit (e.g. the interaction of particles with the walls), a free jet was chosen as the study medium since it is rather well known and documented (e.g. Abramovich 1963).

The purpose of the present study was to measure the velocity distributions of oil droplets of diameter <50 μm suspended in an axially symmetrical, turbulent air jet, in order to gain some insight into the interaction between the dispersed phase and the turbulence of the mainstream.

In order to avoid the difficulties associated with hot wire anemometry or photographic techniques, a Laser–Doppler–Velocimeter (LDV) was used.

2. SINGLE AND TWO-PHASE JETS

An extensive review of the literature pertaining to axially symmetrical, single-phase submerged jets is presented by Abramovich (1963). The jet is divided into three parts: the potential core, the transition region, and the main region. In the latter the jet is considered to be fully developed such that the dimensionless velocity distributions in different cross sections are self similar.

The velocity distribution in the fully developed region was given by Reichardt (1943) for an axisymmetrical jet as:

$$\frac{\bar{u}}{\bar{u}_c} = \frac{1}{2C(x/D)} \mathrm{e}^{-((1/\sqrt{2}C)(r/x))^2} \qquad [1]$$

where $\bar{u}$ is the time-average velocity at a point (r, x) in the jet: $\bar{u}_c$ is the centerline velocity at $(0, x)$; D is the diameter of the nozzle outlet; x is the distance from the nozzle outlet and C is an empirical constant. Values of $0.071 < C < 0.080$ are found in the literature. A value of $C = 0.0713$ has been determined experimentally for an experimental set-up similar to the one used here (Hetsroni & Sokolov 1971). Note that [1] applies only for $x/D > 8$ or so.

The two-phase jet has also been studied previously, even though the results are inconclusive.

Laats (1966) experimented with a circular dusty air jet, with a loading ratio $0 < x < 1.0$ and with particle diameter ranging from 20 to 60 μm. His experimental results indicate that the velocity decay along the centerline is smaller and the velocity profiles are narrower than for a single-phase jet. These phenomena are proportional to the loading ratio.

Goldschmidt *et al.* (1972) used hot wire anemometry to study two-phase jets, assuming that the calibration of the hot wire does not change due to the impingement of the droplets. Their major conclusion is that the transport coefficient of suspended particles is not necessarily equal to that of momentum. They also noted an increasing eddy diffusivity coefficient with particle size—which is physically not understandable.

A hot wire technique was also used by Hetsroni & Sokolov (1971), who measured the velocity (time average and fluctuating components) distributions and the probability density functions in two-phase (air-droplets) jets. Their conclusions are that the time-average velocity distribution can be described by a Gaussian curve, with a spreading coefficient different from the one used for a single phase jet. They further concluded that the droplets cause suppression of turbulence in the dissipation range.

Abuaf & Gutfinger (1971) studied the motion of a single solid particle in a circular air jet, using a photographic technique and particles of 250–400 μm.

Brusdeylins (1966) investigated a turbulent axially-symmetrical horizontal air jet, loaded $(0.1 < x < 0.9)$ with aluminum oxide particles (88–105 μm). His experimental results are essentially in agreement with those mentioned previously.

3. EXPERIMENTAL

The experimental set-up is described by Hetsroni & Sokolov (1971). It includes an air jet emerging from a 25-mm diameter nozzle, designed to produce uniform velocity at the outlet. The liquid droplets are introduced into the air flow upstream from the nozzle. The droplets are produced by six injectors positioned symmetrically around the duct. The size of the droplet was estimated to be less than 50 μm, but was not accurately determined. Two 100-mesh screens are placed between the location of injection and the nozzle, to help in obtaining droplets of uniform size.

Previous experimental techniques utilized either hot wire anemometry or LDV.

The use of hot wire technique is somewhat questionable since it may be argued that the calibration of the wire changes from the curve obtained in single phase flow. The Laser–Doppler-Velocimeter is free of all these shortcomings and offers many advantages to the investigation of fluid flows.

Only few applications of the LDV to two-phase flows are known to us. James (1968) pioneered the method but his results are inconclusive and the velocity measurements could not be reported. Einav & Lee (1973) used the LDV to measure particle velocities in a laminar sublayer. Carlson & Peskin (1973) used a LDV for measuring time average velocities of particles and of the gas in a two-phase flow in a duct. They also measured the particle velocities probability densities.

The optical system used in the present study is based on the reference beam mode, as suggested by Goldstein and Kried (1967), and is depicted in figure 1.

The nine track optical bench is placed on a heavy stand which can be moved 2.00 m in the longitudinal direction, and 1.00 m in the transverse direction. The location of the measuring volume with respect to the origin of the jet, can be determined within ±0.0005 m.

The beam of a 5-mW (CW) HeNe laser (Spectra Physics 120) is split into a reference beam (1.5 per cent of the original intensity) and a scattered beam. Both beams are reflected by 0.10 m diameter front coated mirrors and focused onto the measuring volume by two 0.07 m diameter lenses, having a focal length of 0.2 m. The intensity of the reference beam is reduced by a neutral density filter in order to obtain a most efficient heterodyne signal. The reference beam and part of the scattered beam are mixed on a photomultiplier tube (RCA 7326). This tube has an efficiency of 40 per cent at a wave length of 6328 Å, an amplification of 10^5, a very short response time, and is operated with a 1500 V high voltage supply. The photomultiplier tube is located 0.30 m from the measuring volume and is shielded by two 0.007 m pinholes, positioned 0.1 m apart. The output from the photo-

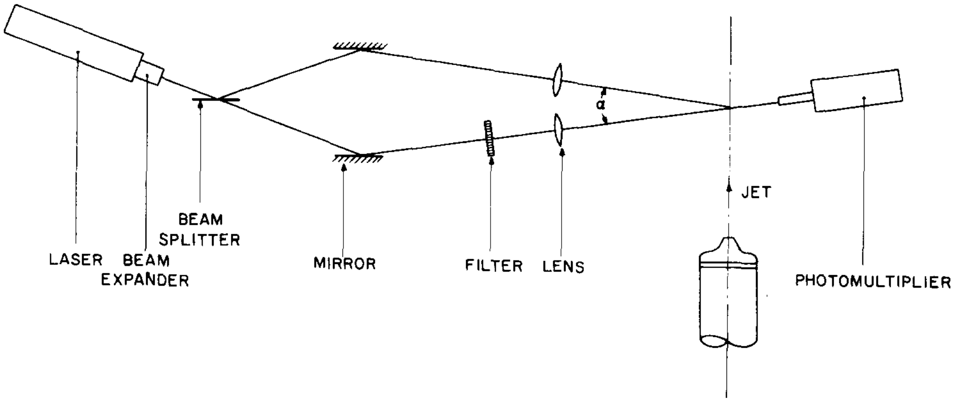

Figure 1. Scheme of optical system.

multiplier is amplified (HP 462 A), filtered (Krone Hite high pass filter 315 A), and fed into a spectrum analyzer (Tektronix IL5, IL10 and IL20).

The calibration of the LDV was ascertained by checking the linear velocity on a disc rotated by means of a variable speed DC motor. A calibration accuracy of 2 per cent was attained. Later the laminar velocity distribution in a 0.03 × 0.03 m conduit was measured by means of the LDV. The expected parabolic profile was obtained with an accuracy of 3 per cent.

The air velocities in the jet were also measured by means of hot wire anemometry. Axial velocity distributions were recorded at $x/D = 10$, 15, 20 and 25. Also measured was the axial velocity decay along the centerline of the jet, up to a distance of 29 outlet nozzle diameters D. The air velocity at the outlet ranged from 10 to 30 m/sec.

The decay of the axial velocity of the droplets along the centerline of the jet was measured up to 19D from the outlet. Droplet axial velocity distributions were also measured at $x/D = 8$, 10, 12 and 14. The low volume concentration ratio of the droplets, 2×10^{-6}, to 6×10^{-6}, resulted in a favorable signal to noise ratio with a half angle of 4° between the reference and scattered beams.

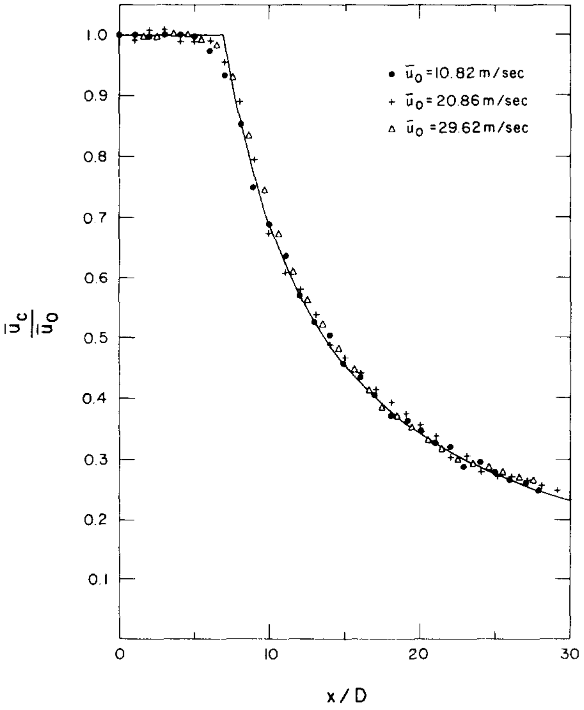

Figure 2. Axial velocity distribution in an air jet.

4. RESULTS AND DISCUSSION

In figure 2 the distribution of the ratio of the time average velocity along the centerline of the single-phase jet $\bar{u}_c$ to the outlet velocity $\bar{u}_o$ is depicted versus the distance from the nozzle outlet (of diameter D). The line best fitting the data is

$$\frac{\bar{u}_c}{\bar{u}_o} = \frac{6.98}{(x/D)} \qquad [2]$$

which is equivalent to a spreading coefficient similar to the one obtained by Hetsroni & Sokolov (1971), i.e. $C = 0.071$.

The distribution of the time-average axial velocities in the single-phase jet is depicted in figure 3 for various distances x/D downstream from the nozzle outlet. The agreement with Reichardt's model [1] is good.

In figure 4 is shown the axial velocity of the droplets along the centerline of the jet, as obtained from the LDV measurements. These data are compared with the axial velocity of the air jet (in the absence of droplets) of figure 2. It is seen from the figure that close to the exit the droplets have 5–9 per cent lower velocities than the air jet, but that the velocity of the droplets decays at a lower rate than that of the air. This is most likely due to their higher inertia. At a distance of about $20D$ downstream the velocity of the droplets is some 7 per cent higher than the air jet at the same location.

In figures 5–8 the dimensionless axial velocity distribution of the droplets is depicted at distances $x/D = 8$, 10, 12 and 14 downstream, for various outlet velocities. Also in the figures are shown the dimensionless velocity distribution of a single-phase air jet. The data indicate that the velocity distribution of the droplets is narrower than the corresponding distribution of the air jet.

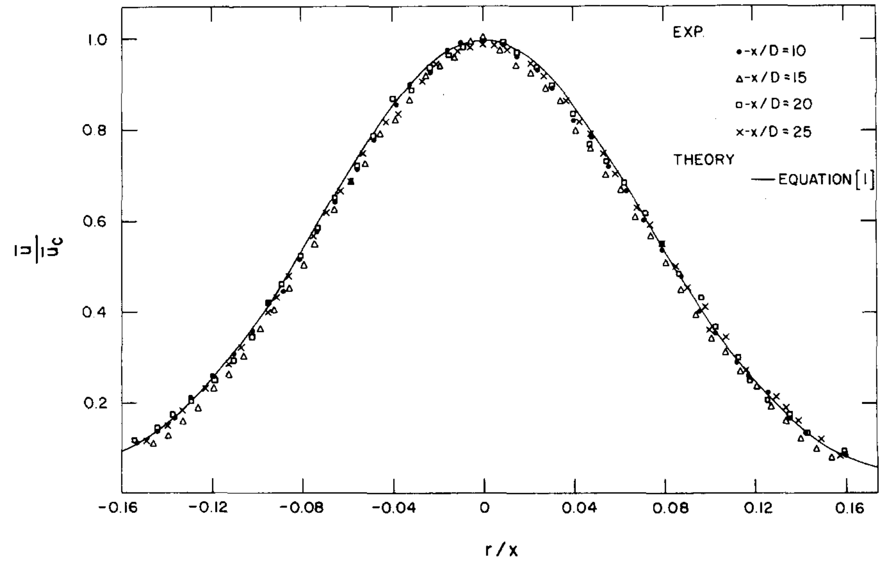

Figure 3. Velocity profiles of air jet.

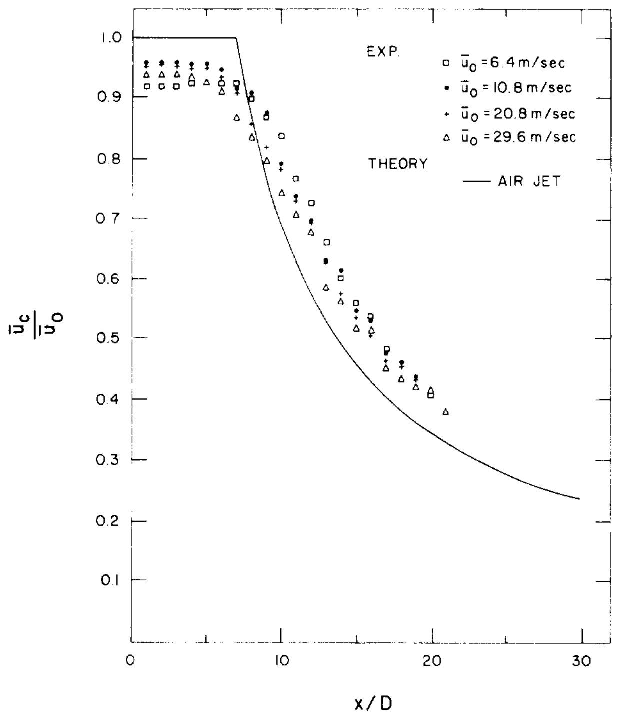

Figure 4. Droplets' axial velocity distribution in a two-phase jet.

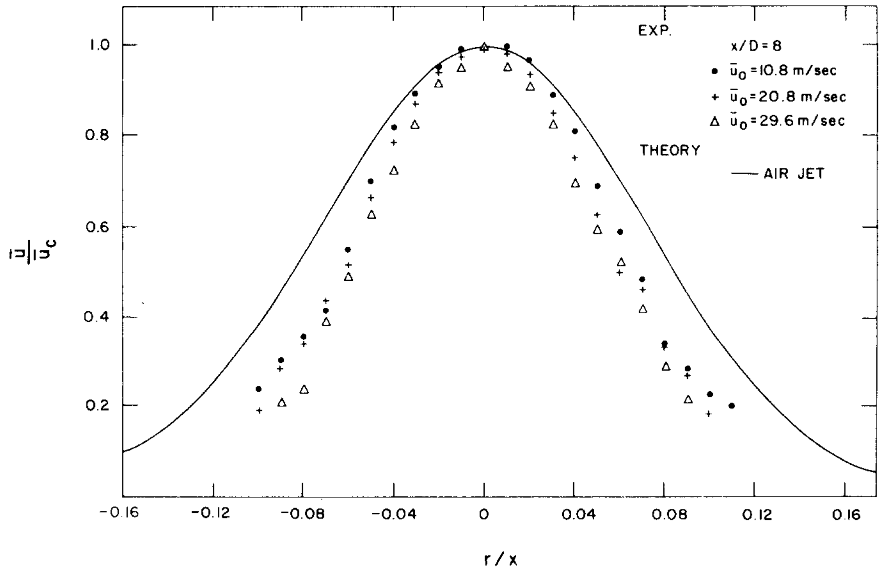

Figure 5. Droplets' velocity profiles in a two-phase jet.

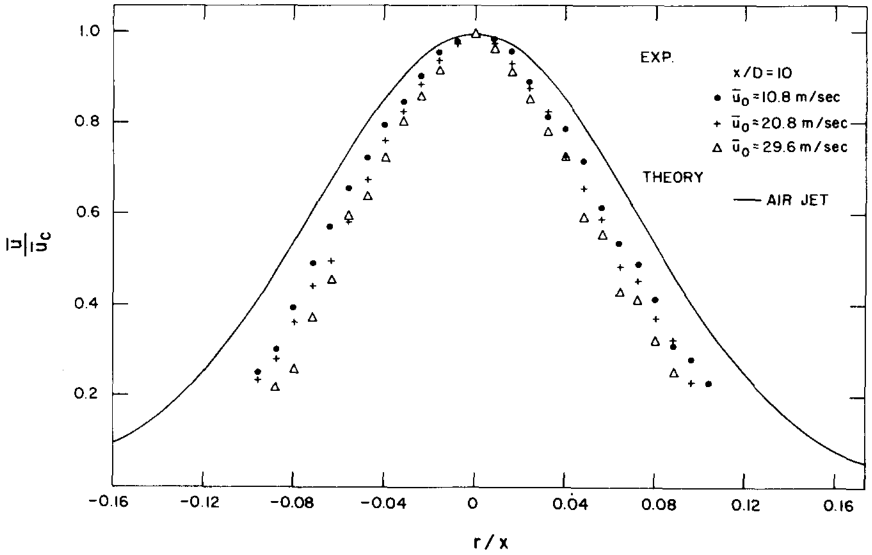

Figure 6. Droplets' velocity profiles in a two-phase jet.

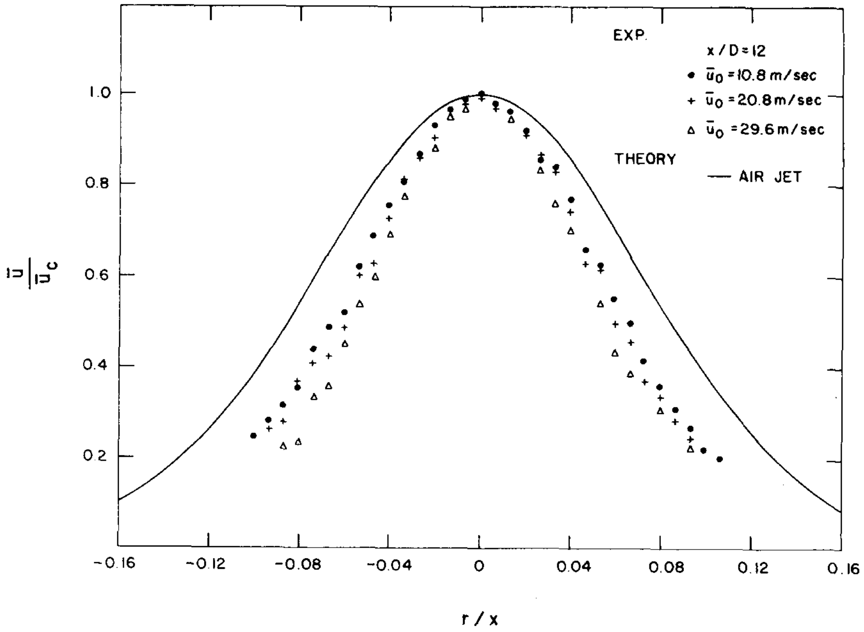

Figure 7. Droplets' velocity profiles in a two-phase jet.

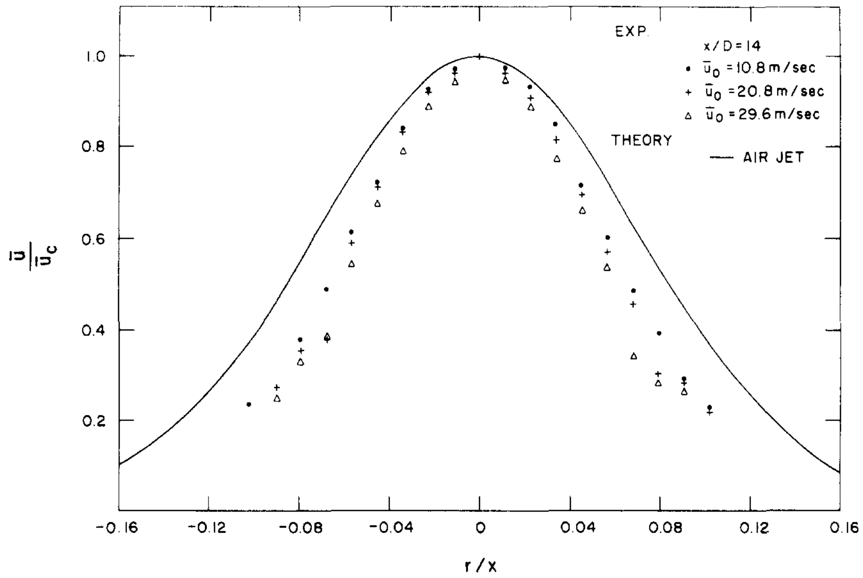

Figure 8. Droplets' velocity profiles in a two-phase jet.

The same data are plotted in figure 9, where the velocity distributions at various cross sections are shown at the same outlet velocity. The data clearly indicate that the velocity profiles of the droplets are self similar.

In figure 10 the velocity decay along the centerline of the jet as measured here, is compared with previous studies. For the single-phase jet the curves are quite parallel, but differ

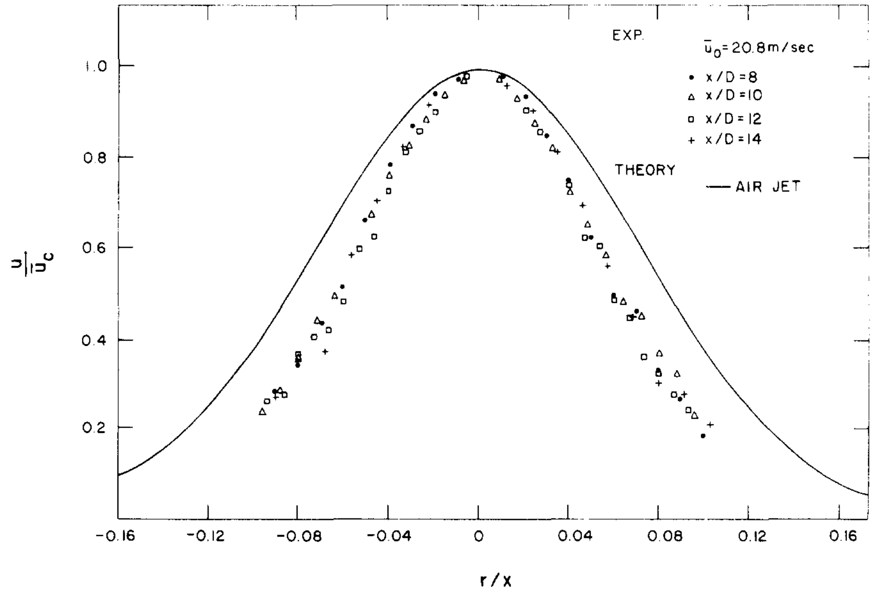

Figure 9. Droplets' velocity profiles at different cross sections.

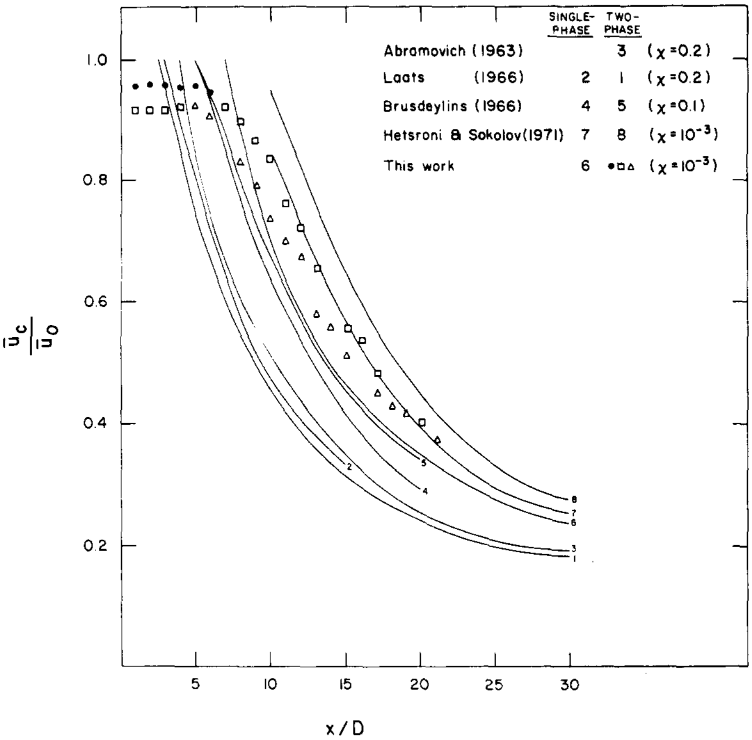

Figure 10. Comparison of axial velocity distribution in a single-phase and two-phase jet.

considerably in the length of the potential core. The fact common to all data sets is that the velocity along the centerline of the two-phase jet (either the velocity of the air or that of the droplets), is higher than the corresponding value in the single-phase jet.

A similar comparison between the distributions of the dimensionless axial velocities with respect to the dimensionless radial distance from the centerline ($r_{1/2}$ is the jet half width) is shown in figure 11, together with our experimental data. The agreement between the data sets is quite satisfactory and is less than 6 per cent. The difference between the velocity distributions is better demonstrated by means of the widening angle of the jet, i.e. the angle between the centerline and the half width of the jet. This is summarized in table 1. Again, in all data sets the two-phase jet is narrower than the single-phase, even though there are discrepancies between the data.

Table 1. Spreading angle of single-phase and two-phase jets (χ is the loading ratio of the dispersed phase)

Source	Single-phase	Two-phase
Abramovich (1963)	—	7° 40′ ($\chi = 0.2$)
Laats (1966)	9° 10′	8° 20′ ($\chi = 0.2$)
Hetsroni & Sokolov (1971)	9° 30′	8° 20′ ($\chi = 0.001$)
This study	9°	8° ($\chi = 0.001$)

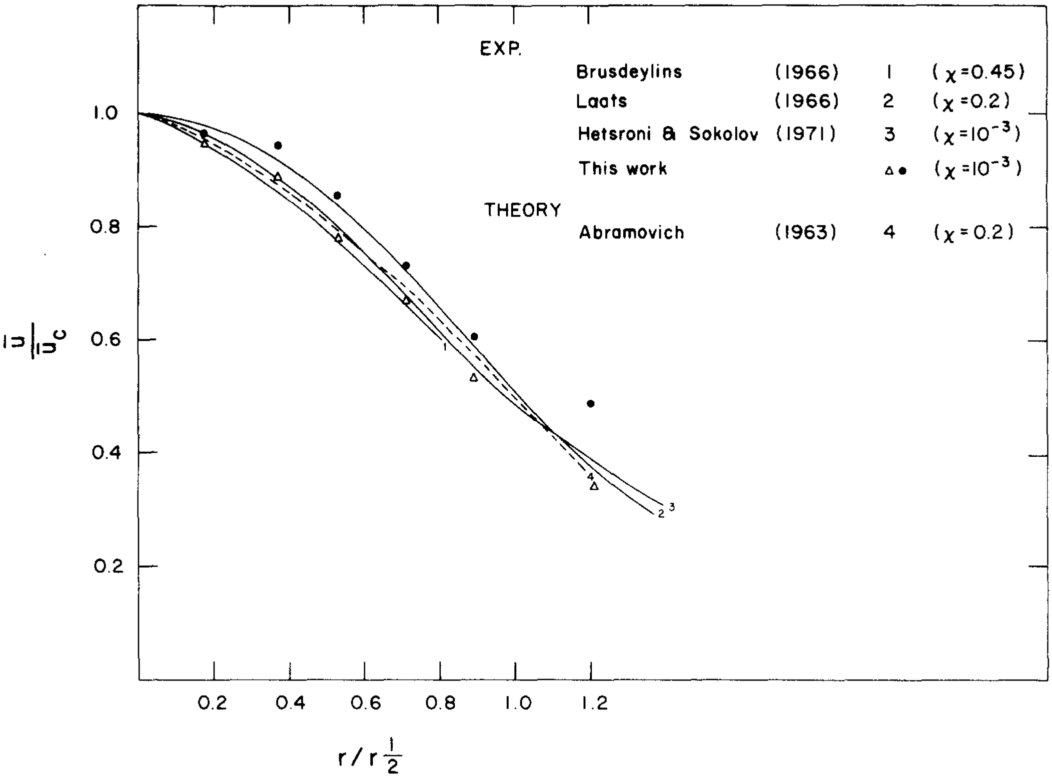

Figure 11. Comparison of velocity profiles in a two-phase jet (χ is the loading ratio of the dispersed phase).

5. CONCLUSIONS

The velocity distribution of oil droplets, with diameters less than 50 μm, suspended in a turbulent axially symmetrical air jet was measured by means of a Laser–Doppler-Velocimeter.

Comparing the results to the velocity profiles of a single-phase jet one can conclude:

(a) The velocity distributions of the droplets are self similar and are well described by [1] with a spreading coefficient $C = 0.050$–0.058.

(b) Two-phase jets are narrower than the single-phase, under similar conditions.

(c) Close to the outlet nozzle in the potential core, the droplet velocities are 5–9 per cent lower than the corresponding velocities in a single-phase air jet. At about eight nozzle diameters downstream the corresponding velocities are equal. Further downstream the axial velocities of the droplets decay at a lower rate than the corresponding air velocities.

(d) The results of this study agree qualitatively with the results of previous studies.

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Résumé—Le mouvement de gouttelettes d'huile dans un jet d'air circulaire turbulent est êtudiê experimentalement. La connaissance directe de la vitesse moyenne des gouttes est obtenue à l'aide d'un Laser Doppler. Les profils des vitesse moyenne des gouttes sont mesurés le long de l'axe du jet et transversalement. Les résultats sont comparés avec ceux de l'expansion d'un jet dêpourvu de gouttelettes.

Le nombre de Reynolds du jet est dans la gamme 10^4–10^5, les gouttelettes ont un diamëtre de 50 μm et moins et la concentration volumique de l'huile dans l'air est de 10^{-6}.

A la sortie du jet, la vitesse de l'air est supêrieure a celle des gouttes; dans la rêgion d'ecoulement établi on trouve qu'en un même endroit, celle des gouttes est supêrieure ă celle du jet. La distribution radiale de la vitesse des gouttes est affine en chaque section et, pour un même endroit, leur vitesse est inférieure à celle d'un jet dépourvu de gouttelettes. La vitesse des gouttes décroit le long de l'axe du jet moins rapidement que celle de l'air le long du jet dépourvu de gouttelettes, et pour une meme vitesse d'échappement, le jet diphasique est plus êtroit que le jet libre immergé.

Auszug—Die Bewegung von Oeltropfen in einem runden turbulenten Luftstrahl wird experimentell untersucht. Direkte Information ueber die durchschnittliche Tropfengeschwindigkeit wird mit Hilfe eines Laser-Doppler-Geschwindigkeitsmessers erhalten. Durchschnittsprofile der Tropfengeschwindigkeit werden laengs der Strahlachse und quer zu ihr gemessen. Die Ergebnisse werden mit der freien Strahlausbreitung verglichen.

Die Reynoldssche Zahl des Strahls liegt im Bereich von 10^4–10^5, die Tropfendurchmesser sind 50 μm und darunter, und die Volumenskonzentration des Oels in der Luft ist 10^{-6}.

Im Strahlaustritt ist die Geschwindigkeit der Luft hoeher als die der Tropfen; im Gebiet des entwickelten Strahls wird eine Tropfengeschwindigkeit gefunden, die Luftgeschwindigkeit im Freistrahl an derselben Stelle uebersteigt. In radialer Richtung sind die Geschwindigkeitsprofile der Tropfen einander aehnlich, und die Tropfengeschwindigkeit ist niedriger als die Luftfreistrahlgeschwindigkeit and der gleichen Stelle. Laengs der Strahlachse nimmt die Tropfengeschwindigkeit langsamer ab als die Luftgeschwindigkeit im Freistrahl, und der Zweiphasenstrahl ist enger als der mit gleicher Austrittsgeschwindigkeit in ruhende Luft ausstroemende Luftfreistrahl.

Резюме—Эксперименталъно исследовалосъ движение капелек масла в крчглой в тчрбулиэованной воэдчшной стрче крчглого сечения. Получены прямые сведения о средней скорости капедек посредством лазерного скоростемера, основанного на эффекте допплера. Распределение средних скоростей капелек измерялосъ вдолъ и поперек о си струи. Резулътаты сравнивалисъ со раскрытием свободной струи.

Порядок величин критерия Рейнолъдса для данной струи со ставлял 10^4з10^5, диаметр капелек был порялка 50 мк, а объемная концентрация масла в воздухе равнялась 10^{-6}.

У корня струи скоростъ воздуха выше, чем скоростъ капелек, а в ее развитой области найдено, что скоростъ капелек болъше, скорости струи свободмого воздуха (в том же месте). В радиалъном направлении распределение скоростей капелек аналогично, и скоростъ капелек ниже, скорости свободной воздушной струи в том же месте. Скоростъ капелек затухает вдолъ о си струи медленнее скорости воздуха в свободной струе, и двуфазная струя уже затопленной струи чистого воздуха при той же скорости истечения.