ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

FINAL REPORT

Contract N6-ori-071(11)

Office of Naval Research, Department of the Navy

MIXING OF FLUID STREAMS

by
Arnold Kivnick
and
H. F. Johnstone

URBANA, ILLINOIS
September 1, 1953

Engineering Experiment Station

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Final Report
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Historical Background

At the close of World War II, it was foreseen that many of the new developments in military items required applications of the principles of fluid dynamics and that research in this field would be fruitful in providing a better understanding and new principles on which further applications could be developed. Thus, the Office of Research and Inventions of the Navy Department established Contract N6-ori-971, Task Order XI, with the Engineering Experiment Station of the University of Illinois to investigate certain aspects of mixing and transport in high velocity fluid streams. The work was started on June 1, 1946. The contract has been extended by the Office of Naval Research (successor to ORI) to the final termination date of December 31, 1953. The total estimated cost of the contract is $106,340.

The objects of the work have remained essentially unchanged in the seven and one half years, but the conflicting pressures of personnel and financial requirements have necessitated occasional changes in the administrative machinery of the program and in the details of the problems under study. During the period October 1, 1950 to December 31, 1951, when ONR was unable to provide the necessary support, the Biological Division of the Army Chemical Corps supported the program under Contract No. DA-18-064-CML-445. From October 1951 until the termination of the contract, the program was supported jointly by the Office of Naval Research and the Flight Research Laboratory of the U. S. Air Forces.

Personnel

For the Navy, scientific supervision of the program was handled by the following persons in chronological order: Comdr. L. Slack, Planning Division, ORI; Comdr. John J. Baronowski, Planning Division, ONR; Mr. C. A. Lejonhud, Planning Division, Fluid Mechanics Branch, ONR; Dr. G. V. Schliestett, Fluid Mechanics Branch, ONR; Mr. P. E. Mullowney, Fluid Mechanics Branch, ONR; Dr. B. Bromborg, Mechanics Branch, ONR; and Dr. F. J. Weyl, Mechanics Branch, ONR. The contract has been administered by the Chicago Branch Office, ONR. Administrative details were handled by Mr. F. X. Finnigan, Resident Representative of the ONR in Urbana.

For the University of Illinois, the business aspects of the program were handled by Mr. C. C. DeLong, Bursar of the University. From 1946 to 1950, the technical direction of the contract was provided by Professor H. F. Johnstone, by Professor E. W. Comings during 1950 and 1951, and by Professor Johnstone from September 1951 until the termination of the contract. During the first year of the contract, Dr. H. G. Drickamer was coordinator of the research and gave direct supervision to the work. These duties were taken over by Dr. L. G. Alexander from September 1947 to February 1950. Dr. Arnold Kivnick supervised the program under the general direction of Professors Comings and Johnstone from October 1950 to August 1952. All the above were on the staff in Chemical Engineering at the University of Illinois.

Dr. Thomas Baron served as consultant to the program from 1948 until

1951, without remuneration. During 1951 he also shared with Dr. Kivnick the direction of the experimental studies being carried on by the graduate research assistants. Dr. Alexander served as a consultant during the summers of 1950, 1951, and 1952, and prepared many of the technical reports. Professor J. W. Westwater served as Research Associate on the program during the summer of 1952.

Mr. Joseph C. Frommer, a consulting electronics engineer, made valuable contributions to the work by designing a sensitive hot-wire anemometer used in the experimental studies.

Most of the experimental work and many of the fundamental developments were contributed by research assistants. The following graduate students in Chemical Engineering were employed as assistants on the ONR contract: Thomas Baron, H. A. Cataldi, C. L. Coldren, R. D. Danielson, E. L. Grimmett, R. W. Kunstman, A. F. Limper, J. E. Nowrey, E. E. Polomik, J. E. Romano, M. C. Tassler, J. F. Taylor, and E. A. White. A. F. Spero, a graduate student in Electrical Engineering, was employed in the construction of the hot-wire anemometer. Also working on the program under the Army Chemical Corps Contract No. DA-18-064-CML-445 were E. H. Bollinger, O. J. Elgert, and E. D. Henze, graduate students in Chemical Engineering. Undergraduate students who worked as assistants were D. Hacker, R. W. Harris, A. K. Mills, R. Scharmer, E. Smith and E. A. White.

Objects and Program

The proposal on which the original project was based was entitled "Investigation of Mixing of Fluid Streams". The objects of the work were stated as follows: "To obtain and correlate information on the mixing of fluid streams under commonly used conditions". The correlations were to be based upon the conservation relationships for mass, energy, momentum and heat, and the transport equations for heat, matter and momentum. Empirically determined equations were to be used where necessary. The conditions to be studied were as follows:

1. Gas jet discharging into stagnant gas
2. Other combinations of jet and ambient fluids
3. Impinging jets
4. Mixing of streams in pipes or ducts
5. Flow of fluids in spiral motion

During the period when the Army Chemical Corps contract was in effect, the program was continued in full. When the partial support of the Flight Research Laboratory was secured in 1951, the program was enlarged to include "Fundamental mixing investigations, the results of which would be applicable to the eventual design of jet pumps, jet augmentors, ducted rockets, and induction wind tunnels".

Research Results

In evaluating the results of a program of this nature, a measure of the effectiveness lies in the reports and published scientific papers in which the fruits of the research are made known. The results of this program are contained in the several reports that have been submitted. There have been fourteen technical reports, designated serially T. R. 1 through T. R. 14, in connection with Contract No. N6-ori-071(11). The seven technical reports issued in connection with the Army Chemical Corps Contract DA-18-064-CML-445 were designated serially T. R. CML-1 through

T. R. CML-7. Research results of lesser importance have been reported in six Technical Memoranda in connection with the Quarterly Progress Reports and the Final Report. Many of the technical reports have been published in modified form in scientific journals. Finally, many of the graduate students employed as research assistants on the program have presented their results as theses in partial fulfillment of the requirements for advanced degrees in the Graduate College of the University of Illinois. These are on file in the Library of the University.

The research results will be discussed here briefly to show the accomplishments and development of the work.

I. Gas Jet Discharging into Stagnant Gas

Studies under this heading constitute the greater part of the program. They will be considered in two parts: Theoretical and Experimental.

A. Theoretical Studies

Early attempts by Prandtl and others to develop a model by which the behavior of the free turbulent jets could be explained resulted in unwieldy equations requiring numerous empirical constants. Reichardt[1] observed empirically that the Gaussian error curve provides good correlation for free jet data, and investigated the mathematical assumptions necessary for such functions to provide solutions to the equations of motion.

In the first technical report on the contract (1), Baron noted the analogies between the dynamic behavior of fluids and the processes of mass and heat transfer occurring in them, believing that a solution to one type of transfer problem might provide simultaneously the solution to

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[1] Reichardt, H., "New Theory of Free Turbulence", Z. ang. Math. u. Mech. 21, 257 (1941), Roy. Aero. Soc. J. 47, 167 (1943).

others. He chose to consider turbulent transport phenomena from the probability viewpoint, as distinguished from the mechanistic view of Prandtl. He hypothesized that the momentum flowing from a differential area is distributed in planes perpendicular to the direction of mean flow in a manner analogous to the distribution of particles diffusing from a point source according to Fick's law. Utilizing the work of Taylor[2] to evaluate the mean square deviation of the position of such particles from the mean, he obtained equations identical with those found previously and independently by Reichardt.

Alexander adopted the statistical approach suggested by Baron, and calculated the velocity field adjacent to the source of a turbulent free jet (3). It was recognized that Baron's statistical method achieved the same result as Reichardt's treatment, i.e., linearization of the equations of motion. Thus, the principle of superposition was applicable. The analogies between the transport of momentum, mass, and heat were noted and the expressions already developed for the transport of momentum were extended to the transport of heat and mass (5,32).

Alexander summarized the previous work on free turbulent jets, and showed that the vorticity transport theory of Taylor[3] could be employed to yield equations similar in form to those derived earlier by Reichardt and by Baron. He extended his treatment to the plane jet and the slit jet, as well as the round jet previously handled, and found that the same equations applied to all three cases, differing only in the value of the single empirical constant present in the equations (13).

Working with the equations obtained as above, Kivnick derived

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[2] Taylor, G. I., Proc. London Math. Soc. 20, 196 (1921)
[3] Taylor, G. I., Proc. Roy. Soc. 135A, 685 (1932)

expressions for the transport of momentum, heat and mass for the case of a turbulent jet discharging into a moving stream (16). He showed that, for this case, one could predict *a priori* that the empirical constant in the free-jet equations (called the "spreading coefficient") should be a function of the ratio of the initial velocity of the jet and the velocity of the moving stream, and should vary from zero when the ratio was unity to a maximum value as the velocity of the moving stream approached zero. The experimental data of Forstall and Shapiro[4] were adduced as experimental verification.

Baron employed the equations for free jets previously obtained, in developing a theory for the behavior of the turbulent diffusion flame, which permits prediction as to the size and shape of such flames within the bounds of engineering requirements (31).

B. Experimental Studies

An extensive program of experimentation involving free jet systems has been carried out. All experiments were in the subsonic velocity range. In the earliest work by Cataldi (38), a free jet of nitrogen was discharged into an entrainer into which air was drawn by entrainment. The gas stream in the entrainer was passed through a partially opened valve and a rotameter by which the total gas flow was measured. The entrainment ratio was determined by analyzing for the oxygen content of the gas flowing through the rotameter, from which the ratio of entrained air to the primary jet fluid, nitrogen, was calculated. This study was intended to establish the effect upon the entrainment ratio exercised by such variables as jet velocity, jet shape, entrainer shape, the distance between the jet and the entrainer, and the internal resistance of the entrainer.

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[4] Forstall, W., and Shapiro, A. H., *J. App. Mech.* 17, 399 (1950)

Only qualitative answers to a few of the above questions were obtained, and the necessity for a program on free jets without the added complication of the entrainer was clearly shown.

Grimmett studied the effect of velocity on the flow properties of free jets (43). He used an impact tube to measure radial and axial velocity profiles at different nozzle velocities, and found the profiles to be independent of velocity within the range studied. Taylor, investigating the radial profiles as a function of the axial distance from the jet (51), observed three distinct regions with different flow characteristics. At distances greater than ten nozzle diameters, the velocity profiles were of similar shape, and were generalized to a single normalized profile. Taylor, Grimmett, and Comings (2,6,36) presented the above experimental results and discussed the transport of momentum and energy calculated therefrom. The data obtained from these investigations were correlated empirically, but the form of the correlations closely paralleled the equations deduced by Baron and Alexander (5,32).

The theoretical studies indicated the existence of three types of similarity in the flow properties of free jets: (a) geometric similarity, i.e., successive profiles of momentum flux are similar; (b) dynamic similarity, i.e., the radial momentum flux profiles are of the same shape, regardless of the discharge velocity; and (c) dimensional similarity, i.e., the radial momentum flux profiles are of the same shape, regardless of the nozzle diameter. The experiments of Taylor (51), Grimmett (43), and Polomik (48), respectively, established the existence of all three types of similarity.

Alexander showed experimentally that his equation describing the momentum flux distribution in the region adjacent to the source of a free jet agreed reasonably well with the measured values (3). Taylor found that the exact form of a nozzle and the level of turbulence in the jet issuing therefrom affect the flow pattern only close to the jet (52), indicating that the turbulent shear forces which become effective at distances greater than one nozzle diameter have a far greater effect upon the ultimate flow pattern than does the initial nature of the flow.

Grimmett (44) mapped the velocity distribution of four different systems: a single nozzle discharging air to the atmosphere, two parallel nozzles discharging to the atmosphere, a single nozzle discharging adjacent to an infinite flat plane parallel to the jet axis, and a nozzle discharging into a straight duct. He then attempted to use the principle of superposition deduced by Baron and Alexander to predict the velocity distribution in each of the complex systems from the distribution of the single nozzle discharging into the atmosphere. His data, although agreeing moderately well with the predictions, are a clear indication that the statistical approach of Baron does not tell the whole story of multiple jet systems, though it serves very well for the flow fields of a single jet at a distance from the nozzle, and is adequate to predict the flow pattern close to the nozzle of a single jet, with the aid of the principle of superposition.

Alexander, Baron and Comings (8) presented a resumé of the literature on free jets, and a discussion of the experimental studies described above. The same authors revised that report and included all the experimental studies on free jets in a Bulletin of the Engineering Experiment Station (28). Alexander also prepared a bibliography on free jets and ducted jets (14).

II. Other Combinations of Jets and Ambient Fluids

At the time the program was proposed, it was intended that this phase of the research should consider four combinations: A liquid jet discharging into a stagnant liquid, a non-condensing gas jet discharging into a liquid, a condensing gas jet discharging into a liquid, and finally a liquid jet discharging into a gas. The first of the above systems was investigated by Albertson et al[5] and was found to behave very like the system of a gas jet discharging into a stagnant gas. The second and third items above presented problems in instrumentation not readily amenable to solution. It was therefore decided to restrict the work under this heading to the fourth item, and a study of atomization of liquid jets thus ensued. This study was later enlarged to include an investigation of spray dryers.

A. Theoretical Studies

Baron's work on atomization (4) was intended not so much to provide a quantitative relationship upon which design calculations might be based, as to examine the several theories of drop formation together with the mathematical relationships resulting from them and to choose that combination of theories which contained the least amount of contradiction. He arrived at the following conclusion: An initially spherical drop, placed in an air stream, is deformed by frictional drag and inertial forces. The deformation is accompanied by an increase in surface. Surface tension tends to restore the drop to its initial spherical shape. There results a tendency toward oscillation about the spherical equilibrium configuration. In order that the oscillation may proceed without opposing the drag and inertial forces, the drop is forced to rotate in synchronization with its oscillations. In consequence, centrifugal forces are set up which further

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[5]Albertson, M. L., Dai, Y. B., Jensen, R. A., and Rouse, H., Proc. Am. Soc. Civil Eng. 74, 1471 (1948).

increase the tendency toward deformation. Because of the synchronism, the system is one of forced vibrations with viscous damping. In such a case, there exists a critical degree of deformation beyond which the drop cannot return to its spherical form, but disintegrates instead.

The mechanism postulated for the disintegration is as follows: The distorted droplet takes the form of an oblate spheroid. When the critical deformation is reached, centrifugal force tends to force the liquid toward the periphery of the drop, yielding a shape like that of a doughnut with a thin web persisting perpendicular to the axis. The thin web is then blown out, and the distorted droplet takes on the shape of an inverted cup with a heavy edge and an extremely thin base. Disintegration occurs as the thin base tears. Evidence of this mechanism was found in the observations of Lenard[6], who showed that a drop consists electrically of a negative layer at the surface paralleled by a positive layer farther inward. In consequence of the pattern of forces previously described, positive charges are forced toward the heavy edge of the cup-shaped droplet, and the negative charges concentrate in the thin base. The droplet is then "blown" apart, with the positive charges being present in the large droplets formed from the liquid at the edge, and extremely fine negatively charged droplets formed from the thin base.

Kivnick (18) considered the coalescence of droplets under the influence of turbulent jets. He started with an equation previously derived to predict the rate of collision of colloidal particles under the influence of a velocity gradient, and obtained an expression for the rate of collison of droplets. He found that the rate was proportional to the

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[6]Lenard, *Ann. Phyzik* 44, 484-87 (1915).

concentration of droplets of the size being considered, the ratio of the volumes of the discontinuous and continuous phases, and the velocity gradient, which is related to the fluctuating velocity in a turbulent system.

The rate-of-collision equation was applied to the case of coalescence of droplets from a two-fluid spray nozzle in two ways. First, a method was found to estimate the upper limit of coalescence by combining the rate equation with equations for the momentum profiles of free jets, ignoring the effects of the jet in diluting the spray, and applying a highly simplified view of turbulence distribution within the jet. An equation resulted which states that the fraction of droplets of a given size remaining at a given distance from the nozzle is proportional to the distance raised to an exponential power proportional to the product of the Reynolds number for the gas flow through the nozzle times the ratio of the volumes of the discontinuous and continuous phases.

A more precise expression for the extent of coalescence was obtained by setting up differential equations expressing conservation of droplets of a given size, conservation of all droplets, and conservation of momentum. The equation for conservation of droplets of a given size involves the rate-of-collision equation, which in turn is a function of empirically determined turbulence data. The concentration of droplets of a given size at any point can be computed by simultaneous solution of the three differential equations mentioned. Because of the complexity of the equations, and the fact that the turbulence data cannot be reduced readily to analytic forms, solution of the equations by analytical means is not possible. It was suggested that the solution might be possible by converting the equation for conservation of droplets of given size into a finite difference equation, and then solving by an iterative procedure. The reference report includes details of the proposed finite difference equation and its possible solution by iteration.

B. Experimental Studies

The atomization of liquids by injection into high velocity gas streams in a venturi atomizer was studied by Limper (47). He injected oil and water into venturi throats of different diameters and varying exit shapes, and studied the effect of air velocity and the other variables on the size distribution of the resulting drops. His results were rendered questionable by the fact that appreciable amounts of atomized liquid collected in the diffuser section of the venturi and were re-atomized by the air stream. His drop-size distributions were taken, therefore, not merely from the population of droplets formed by atomization at the throat but also from those formed by re-atomization. The inability to distinguish between the two vitiated the value of the study.

At this point in the program, it was decided that further concentration upon the study of atomization per se would necessitate such an extensive program of instrumentation development as to prevent further work on other phases of the program. The study of the mechanism of atomization was accordingly terminated, and attention was directed to other properties of spray-jet systems.

Alexander and Coldren (9,29,39) studied the transfer of small water droplets from suspending air to duct walls. Droplets formed in an air-atomizing nozzle were sprayed into a test section, along with air induced by the high-velocity stream from the nozzle. The length of the test section was varied. At the end of the test section a collection rake was used to sample the suspended liquid at nine different points on a diameter. It was found that, in regions close to the nozzle, the profiles of droplet concentration were not at all flat, indicating that the resistance to droplet deposition lies in the main stream itself. In the region farther away from the nozzle, the flow more closely resembled normal pipe flow, and the bulk of the resistance to the movement of the droplets to the wall lies in the laminar film adjacent to the wall. Empirical equations were used to correlate the experimental data in terms of mass transfer coefficients. It appeared that two regimes existed in the system, one close to the nozzle, the other farther away, and that the transition between the two was gradual. The equation showed that the mass transfer coefficients were dependent upon the gas velocity in both regimes, but that both the exponent and the coefficient of the velocity term differed in the two regimes.

Coldren and Comings (21,40) investigated the behavior of a high-velocity spray dryer. It was their intention to construct a device which would atomize a liquid into a gas stream at a high temperature and move the atomized material so rapidly through the high temperature zone that rapid evolution of water might be effected without overheating the material dissolved in the water. A second purpose of the study was to permit an evaluation of the applicability of the equations developed earlier for homogeneous jets to heterogeneous systems. A series of differential equations was set up: one equation stating conservation of momentum, another the conservation of heat, a third the conservation of droplets, a fourth the conservation of water vapor, a fifth the conservation of total moisture, and a sixth the conservation of total energy. By simultaneous solution of the six equations by analytical or numerical means, as required, there can be predicted profiles of momentum flux, temperature humidity, and droplet concentration, which must be checked against observation.

One of the problems encountered in the operation of such a dryer lies in the fact that the dried material must be collected; hence the nozzle must be placed within a duct. When a jet is discharged into a duct (see Section IV), there is a tendency for the jet to spread rapidly until it strikes the wall of the duct. If the jet contains a moist solid, the solid is likely to collect on the walls in the zone of impingement of the jet. In that case, the dried material is exposed to the high temperature for long periods of time, thus defeating the purpose of this type of dryer. It was necessary to seek some means of stabilizing the jet; i.e., preventing its rapid spread. Elgert (42) tried first to allow the jet to entrain sufficient air to prevent spreading. This was not successful. It was then decided to use a forced secondary air stream. Thus, a stream of solution was atomized by injection into a high-velocity air jet at a high temperature; the latter jet discharged into a heated coaxial air stream moving in the same direction as the jet. As indicated by earlier studies on coaxial jets (16), the effect of this system was to stabilize the jet, or to reduce its rate of spread. It was therefore possible to operate the high velocity spray dryer with a forced secondary air stream without the risk of depositing undried solids on the wall of the dryer chamber.

III. Impinging Jets

The work on this subject was limited to an experimental program involving impinging gas jets, mounted at angles of impact varying from 0 to 60 degrees. Baron and Bollinger (17,37) made impact tube traverses for several combinations of angle of impact and relative nozzle velocities, for each nozzle discharging separately and for both discharging together. These experiments were intended to show the degree to which the principle of superposition might be expected to apply. They found that, for the case of parallel nozzles, the principle of superposition gave results within the limits usually demanded in engineering work, for both nozzles operating at the same discharge velocity, and for one nozzle at twice the velocity of the other. However, for the case of nozzles oriented at an angle of impingement as small as 7 degrees, the principle of superposition failed utterly. The authors believed that significant static pressure gradients existed, rendering the Reichardt hypothesis and the principle of superposition deduced from it invalid. They concluded that only by a more fundamental approach to the turbulence problem itself might further progress be made.

IV. Mixing of Streams in Pipes or Ducts

Following the course of action usually employed in this program of proceeding from the relatively simple to the more complex, this problem was attacked as a special case of the free jet: a jet discharging into a duct, or ducted jet. Later experimental studies considered mixing under conditions of so-called normal pipe flow.

A. Theoretical Studies

Using the Reichardt hypothesis, or its equivalent, Baron's statistical approach to the free jet problem, and the principle of superposition deduced from them, Alexander derived equations which were at the same time solutions of the equations of motion and satisfied the boundary conditions for the case of the ducted jet (11,30). These equations permitted the correlation, and therefore presumably the prediction, of momentum flux distribution at various points within a ducted-jet system. The equations so obtained were extended to cover the transport of heat and mass in the ducted jet (12,33 Pt. II).

It has often been observed that in turbulent systems the transport of heat occurs more readily than that of momentum, and the two rates of transport are in the ratio 4/3. In the course of the derivation of the expressions for the transport of heat in the ducted jet, it was found that the spreading coefficient for heat was in the ratio 4/3 to the spreading coefficient for momentum, as expected.

B. Experimental Studies

In the first studies on the ducted jet system, a jet was discharged into a duct such that the temperature of the emergent jet fluid was the same as that of the induced air. Impact pressure traverses were made at several cross-sections along the duct, and the static pressure was measured along the duct wall. These data were satisfactorily correlated by the method developed by Alexander, as described above (11,30). Next, experiments were conducted in which the jet was at a temperature considerably above that of the induced air (15,33 Pt. I, 45). Measurements of both impact pressure and temperature were made. The temperature measurements, performed with the use of a fine thermocouple, fell between the stagnation and free stream temperatures. By taking advantage of the fact that the nozzle used for the jet was designed to give adiabatic expansion, it was possible to determine the coefficient of recovery for the particular thermocouple used, and so to calculate the free-stream temperature, once the thermocouple reading and the impact head were known. The data for the non-isothermal ducted jet were correlated by means of the equations for mass and heat transport in ducted jet systems (12,33 Pt. III).

In both sets of experiments, the same flow system was used. In both cases, it was observed that the momentum flux was abnormally low at distances relatively far from the duct wall, giving rise to speculation that the thick boundary layer whose presence was indicated by the reduced momentum flux was caused by incipient choking in the duct. Choking was defined as the phenomenon which exists when a jet, prevented from entraining the required amount of secondary fluid, sucks back along the duct wall fluid already entrained. Another possible explanation of the thick boundary layer was separation caused by a fairly sharp corner at the point at which the entrained air entered the duct. In order to resolve this question, experiments were carried out using the same duct and jet as before, with the entry for the entrained fluid faired, as for the entry of an induction wind-tunnel. In these experiments (24,41) the thickness of the boundary layer was markedly reduced. It was obvious, then, that regardless of whether the thick boundary layer was caused by incipient choking or by separation at the entry, the faired entry eliminated the difficulty; hence the sharp-edged entry was the cause of the thick boundary layer.

The ducted-jet studies heretofore considered dealt with the distribution of conservable entities within a duct into one end of which a jet was discharged concentrically. Experiments were also conducted to determine the distribution of momentum flux within a duct concentric with a jet located fifteen nozzle diameters from the duct entrance. These data, obtained by Grimmett (44), were correlated by Alexander (23) using the relationships previously obtained (11). The agreement between the data and the correlation in this case is not so good as for previous cases.

The discrepancy is explained as follows: In obtaining the constants for the correlation in the case of a jet discharging directly into a duct, formal integration is possible, yielding precise results. In the case described here, a graphical integration based on the experimental data is required, as well as calculations which involve small differences between large numbers, divided by the squares of small numbers. As a result, discrepancies as large as 20 % were observed.

In response to an ONR request for a study of the behavior of low-velocity jet pumps in which the primary jet was of the order of 2/3 the diameter of the duct, a series of experiments was carried out with such an apparatus. Two questions were raised in connection with such pumps: 1. Is the induction ratio a function of the velocity of the primary jet, or does the pumping efficiency vary with the primary jet velocity? 2. Does the mixing length (i.e., the distance at which mixing of the jet and the induced streams is complete) vary with jet velocity? It was found (25) that the induction ratio remained substantially constant as the jet velocity varied from 50 ft./sec. to 250 ft./sec., and that the mixing length too was relatively little affected by velocity variations.

Alexander's bibliography (14) mentioned previously, includes the ducted jet as well as free jets.

The final studies on flow in ducts were concerned with the Reynolds analogy between the transport of momentum and heat in such flow. Kunstman (46) showed that the criteria for similarity between momentum and heat transport could be stated in terms of the equality of two turbulent cross products, both measurable by means of the hot-wire anemometer. The experimental problems involved in the design of the anemometer are discussed in more detail under "Instrumentation". It was shown (19,46) that the Reynolds expression for turbulent shear in terms of cross-products of turbulent velocity components is subject to experimental verification. The data obtained, although they cannot be taken as convincing proof of the mathermatical similarity between turbulent heat and momentum transport, at least offer confirmation of that similarity.

V. Flow of Fluids in Spiral Motion

No formal studies, theoretical or experimental, were performed under this heading. The development of the instruments prerequisite for such studies did not reach a satisfactory stage until the spring of 1953, at which time the decision to terminate the program was already being made.

VI. Instrumentation

Any experimental program which attempts to achieve accuracy in its measurements must of necessity expend considerable care in examining and calibrating the instruments by means of which those measurements are made. It is frequently the case that experimenters in new fields must develop their own instruments, or exert considerable effort in modifying existing ones to suit their needs.

The most serious instrumentation study undertaken in the course of this program was the development of a hot-wire anemometer suitable for measuring the intensity of turbulence and the cross-products of the axial and radial components of turbulence, and temperature fluctuations. A second development program dealt with a pneumatic thermometer and hygrometer. Finally, an inquiry into the precision of total-head impact tubes posed several questions for which the answers are still unknown.

A. The Hot-Wire Anemometer

At the start of the program, it was recognized that turbulence must play an important role in determining the rate of spread of free jets. Attempts to measure the level of turbulence in such jets were clearly in order, and construction was begun of an instrument capable of making such measurements. Spero (50) built the first hot-wire anemometer used in this program. His instrument was not satisfactory for the purposes of the program because of the high noise level in the early stages of amplification. This type of anemometer operates by measuring fluctuations in the resistance of a fine metallic filament. The temperature of the filament varies because of changes in the rate of heat transfer from its surface caused by variations in the velocity of the gas stream in which the filament is immersed; the temperature variation causes fluctuations in the resistance. The variations in resistance are small, and must be amplified to be measured. However, most amplifiers create small random fluctuations of their own called "thermal noise"; when the thermal noise is of the same order of magnitude as the signal to be amplified, the resulting amplified signal bears an uncertain resemblance to the fluctuation originally fed to the amplifier.

The anemometer used for the studies in this program was designed by Joseph C. Frommer, a consultant employed on the contract, and was built by H. W. Kunstman. The instrument is of the constant-current type, and many of its circuits are modelled on those used by Schubauer and Klebanoff[7]. It is described in References 7, 19, and 46. Reference 7, an operating manual prepared in 1950, has been rendered obsolete by changes in the instrument. A complete wiring diagram is available in Reference 46.

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[7]Schubauer, G. B. and Klebanoff, P. S., N.A.C.A. ACR 5 K 27 (WR W-87) (1946).

The anemometer described here has several unique features. The first stage of amplification has an extremely low noise level-less than one-sixth the magnitude of the smallest signal to which the anemometer is expected to respond. Also, the method used for determining the "compensation" required for the so-called "time-constant" of the wire is novel. Since the hot-wire has a finite mass, however small, it must inevitably lag behind the actual fluctuations imposed upon it by the system in which it is placed. It is necessary, therefore, to provide an electronic means of eliminating the lag. The circuit used for eliminating the time lag, or compensating for it, is a simple resistance-capacitance circuit. However, the determination of the time-constant of the wire, which establishes the amount of compensation required, is a more difficult problem. The description of the circuit used for setting the compensation is beyond the scope of this summary. The method and underlying theory are described in References 19 and 46.

Of equal importance with the electronic aspects of the anemometer is the design and construction of probes. The probes used in these investigations consisted essentially of two tungsten filaments with the supports necessary to give them mechanical stability and electrical continuity. The filaments are electrically independent of each other and are mounted in the form of the letter X, approximately perpendicular to each other. In order that the probes be sensitive to the fine structure of turbulence and create a minimum of disturbance in the region they are intended to measure, it is imperative that they be as fine as possible. The filaments used in these studies were of the finest tungsten wire commercially available, 0.000139 inches in diameter. Their length is about 1/16th of an inch. Each wire must be soldered at its end to the supports. Since soft solder does not adhere to tungsten, two small regions on each filament must be plated with copper. The filaments are so fine as to be virtually invisible to the unaided eye, and are able to withstand very little handling without breakage. Jigs have been developed (19,46) which increase the probability that an attempt at probe-making may succeed.

The probes described above exhibited serious shortcomings. First, since both the wires were fastened to support wires which in turn were connected to a single rigid probe-holder, the entire assembly of two wires had to be built, calibrated, used, and recalibrated as a unit. The failure of either filament at any state of this series of operations immediately terminated the usefulness of the whole assembly, and wasted not only the labor involved in the assembly but the experiments as well. Secondly, the difficulties inherent in fastening the filaments to the supports were so great as to eliminate the possibility of adjusting the orientation of the wires with respect to each ohter. As a consequence, in the few cases in which the probe assembly remained intact through the entire experimental cycle, the inaccuracy in orientation of the filaments decreased the precision of the results appreciably. A method had to be found to replace the Siamese-twin probe assembly with one whose two filaments would be made individually, subject to individual calibration and orientation, with each filament amenable to replacement during operation by another.

Such a probe assembly has been built and is described in References 26, 34, and 49. It consists of individual slant-wire half-probes, with the probe supports of each designed to facilitate the assembly and orientation of two such members into a complete probe assembly. Orientation is performed with the aid of a binocular microscope and a haemocytometer microscope slide of the type used in clinical blood-count studies.

While these instrumentation studies were in progress, it was found advisable to compile a short bibliography on hot-wire anemometry (22) for use within the program, and for limited distribution to persons outside the program who requested copies.

B. The Pneumatic Thermometer and Hygrometer

In the course of experiments on the high-speed spray dryer, attempts were made to measure the humidity within the dryer. The first method used was that of the wet-and-dry-bulb thermometry. In regions where most of the water droplets had already been evaporated, it was almost impossible to keep the wick on the wet-bulb thermometer saturated, on account of the high rate of evaporation from the wick into the gas space. In regions close to the nozzle, the many water droplets present kept the wick saturated, but then it was extremely difficult to make significant dry-bulb measurements. Various shielding schemes came to naught, and the wet-and-dry-bulb hygrometer was given up as a bad job. It was decided that humidity of the air at a given point might be measured by drawing a sample of the air at that point through a weighed container of desiccant, and then metering the dried air under conditions such that its temperature might be measured. The volume of air passing through the desiccant might be determined from the temperature and flow measurements, and the quantity of water removed found from the change in weight of the desiccant. Aside from the question of the precision of such humidity measurements, this method left unsolved the problem of measuring the dry-bulb temperature within the dryer. Such measurements were obviously required for satisfactory understanding of the operation of the dryer.

The method finally chosen was adapted from a device used for measuring the temperature in the exhaust of rockets. In that case, because of the extremely high temperatures involved, no measuring device directly dependent upon the gas temperature had any dimensional stability. The solution consisted of drawing a sample of the rocket exhaust gases through a water-cooled orifice at the end of a water-cooled tube and measuring the pressure downstream of the orifice; the gas sample was then cooled and passed through a second orifice meter at which its temperature was also measured. From the gas rate and temperature at the second orifice were computed the weight rate of gas flow through both orifices; if the molecular weight of the gas was known, the velocity through the first or high-temperature orifice could be computed from the pressure measured downstream of that orifice and the pressure assumed upstream. With the volumetric and gravimetric flow rates through the first orifice known, and the pressure upstream of the first orifice known or assumed, the temperature upstream of the first orifice was calculable from the gas laws.

The instrument was adapted to use in the spray-dryer problem after it had been ascertained that negligible errors would result from the passage of droplets through the orifice. In order to determine the molecular weight of the air passing through the first orifice, the humidity had to be measured. This was accomplished by drawing the air from the second orifice through a desiccant and measuring its flow through a third orifice meter. The difference in the flows through the second and third orifices, suitably corrected for temperature, must be due to the water vapor removed by the desiccant. With the volume of air and its original water content known, it was then possible to compute the air temperature upstream of the first orifice as described above. The instrument is described in detail in References 20 and 40. The development of the pneumatic thermometer and hygrometer required the expenditure of fully a year of effort, and involved an extensive program of study on the behavior of miniature orifice meters. Lack of precise information as to the idiosyncracies of such meters would seriously have limited the accuracy of the final instrument.

C. The Impact Tube

Throughout this program, measurements of velocity at points in various flow fields had to be made. The method employed in making the measurements involved the use of impact tubes. The principle of the instrument is simple and familiar. The open end of the tube, facing into the direction of flow, causes the flow to stagnate, so that the pressure transmitted within the tube is related to static pressure in the flow field plus the kinetic head. If an independent measurement of the static pressure can be made, or if the static pressure is known by some other means, the pressure difference is proportional to the kinetic head. Further, if one assumes that no frictional effects are present, that the fluid is incompressible, and that the level of turbulence at the point being measured is low, the pressure difference may be equated to the kinetic head; that is to say, the constant of proportionality may be set equal to unity. It is common in the use of impact tubes to make all these assumptions. If one divides the pressure difference by the gas density, there results the mean square of the velocity, which, in conditions of low turbulence, is equal to the square of the mean velocity.

Standard impact tubes were used throughout this program. Because it was desired that the experimental results have a high order of precision, however, it was decided that an attempt be made to calibrate the impact tubes, rather than to assume that the constant of proportionality (i.e., the calibration coefficient) was equal to unity. The calibration was performed by placing the impact tube just downstream of the discharge of a calibrated flow nozzle. A measurement of the pressure drop across the nozzle and the upstream temperature gave the volumetric flow through the nozzle. With the area of the nozzle known, and the assumption that the velocity was constant everywhere in the plane of discharge of the nozzle, it was possible to estimate the velocity at the point at which the impact tube was placed. The velocity might be compared with that calculated from the impact head as measured by the impact tube, and a calibration coefficient could be computed. Coefficients were obtained in this way by Grimmett (44), and were reported in (8). The discrepancies between the measured coefficients and unity were great enough to warrant investigation. The explanations had previously been proposed for low impact tube coefficients: (a) at low velocities, a frictional effect was believed to exist, and (b) at high velocities, the compressibility of the gas was too great to be ignored. Modified calibration coefficients were computed on the assumption that only these two effects existed. It was found that the experimental coefficients agreed well with the calculated ones at high velocities, but the disagreement at low velocities was still too great to be ignored. It was postulated that this disagreement was caused by the existence of a slow-moving film close to the wall of the flow nozzle: since the assumption of a uniform velocity in the plane of the nozzle discharge was incorrect, the coefficients computed as a result of that assumption were necessarily incorrect. These findings were reported in a correction to Reference 8, along with the computed values of the impact tube coefficients.

An experimental program was undertaken to provide a check on the postulated explanation for the abnormally low coefficients, and, if possible, to provide a satisfactory method for calibrating impact tubes. These experiments indicated the existence of the slow-moving film near the nozzle wall, and showed that the film thickness diminished as the gas flow was increased. They failed, however, to provide a satisfactory solution to the problem of calibrating impact tubes. The experimental and theoretical investigation of calibration of impact tubes was reported in Reference 27.

An attempt was made to determine the effect of turbulence on impact tube calibrations. Metal grids were placed across the discharge of a flow nozzle, and turbulence was presumably generated within the normally non-turbulent "potential cone" region of the jet from the nozzle. The equations of Dryden et al.[a] were used to calculate the level of turbulence at various distances from the grids. Measurements were made with the impact tube at various points of the flow field, both in the presence of the grids, and without them. It was concluded that the presence of the grids affected either the jet or the impact tube, or both; the effect was quite marked close to the nozzle, and diminished at greater

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[a] Dryden, H. L., Schubauer, G. B., Mock, W. C., and Skramstad, H. K., N.A.C.A. Report 581 (1937).

distances. This investigation was reported in References 10, 35 and 52.

Facilities

The facilities available to the program at the start were those of the Noyes Laboratory of the Chemistry Department and a wing of the old military stables near the campus. The Office of Naval Research made available to the program a Chicago Pneumatic Diesel-driven 500 CFM, 125 lb. per sq. in. air-compressor and an electrically driven 300 CFM Sullivan air compressor. Unfortunately just as the smaller compressor was being installed, a fire destroyed the stables and the Sullivan compressor was badly damaged. The Diesel compressor, however, was not damaged. New facilities were provided in the form of a Quonset hut at the University Airport. This was converted into a laboratory suitable for the studies planned, and was named the Airflow Laboratory. A suitable system of temperature and flow controls was installed, permitting the simultaneous operation of six experimental set-ups. All the studies on free jets, ducted jets and spray dryers were performed at the Airflow Laboratory.

Early studies involving the use of the hot-wire anemometer were also carried on at the Airflow Laboratory. However, the oil content of the air from the compressor was great enough to affect the experiments adversely, and facilities were provided in the new East Chemistry Building where a low-pressure centrifugal blower served as the air source.

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