Engineering Notes

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Heavy Rain Influence on Airplane Accidents

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Introduction

WEATHER has always been a serious element in aviation safety. Even today, with modern weather radar aboard commercial aircraft, improved weather forecasting, and the rapid communicating and updating of existing weather conditions, weather remains a cause or related factor in a high percentage of aircraft accidents. A review of aircraft accident records for the past decade clearly exhibits the necessity of aircraft avoiding the most severe weather environments, such as those associated with thunderstorms. The Eastern 066 accident at JFK in 1975, the Allegheny accident in Philadelphia in 1976, and the Southern accident near Atlanta, Ga. in 1979 all clearly show the necessity of avoiding the severe weather environment, even with today's aircraft. The flight manuals for all commercial airlines clearly warn the pilot to avoid the vicinity of a thunderstorm and, particularly in the landing situation, to avoid penetrating any thunderstorm cell. Nevertheless, the exact location of a thunderstorm cell is not always well known to the pilot who is on final approach. Occasionally, highly turbulent cells are encountered with intense rainfall and low visibility which provide a serious landing hazard to an aircraft. Under such conditions, a go-around maneuver is commonly executed. An adjoining article in this journal titled "The Aerodynamic Penalties of Heavy Rain on a Landing Aircraft" raises the possibility of rain as a causative factor in aircraft accidents, especially those previously attributed to windshear. This Note is designed to apply the results presented in that article to the study of thunderstorm-related windshear accidents.

The Haines and Luers study (Ref. 1) outlined several possible detrimental effects that heavy rain may produce on an aircraft. The momentum of raindrop impacts on an aircraft will extract energy from the aircraft. A water film may form on the airfoil and fuselage which roughens the airfoil, causing a lift and drag penalty due to 1) waves in the film and 2) the cratering of the drops upon impact. The water film on the aircraft will produce a weight penalty directly proportional to its thickness. The UDRI study (Ref. 1) analyzed these sources of penalties and concluded that the weight penalty was negligible for transport category aircraft, the momentum penalty could be significant under extremely intense rainfall rates on the order of 500 mm/h, and drag and lift penalties due to a roughened airfoil could be very significant at rainfall rates in excess of 100 mm/h. The study indicated that an increase in the drag coefficient of the aircraft of from 5 to 30% can occur for an aircraft in a landing configuration merely because the wetted aircraft surface is aerodynamically rough. At high angles of attack, a lift penalty due to roughness can exceed 30%. In addition, the angle of attack at which maximum lift occurs for a roughened airfoil is from 2 to 6 deg less than that for a clean airfoil. Thus a wing that normally stalls at, say, 19 deg may stall at less than 15 deg if it is aerodynamically roughened. Since stall warning devices generally activate at approximately 3 deg less than the clean wing stall angle, it is possible for an aircraft with a roughened wing to stall before the stall warning system activates. Once stall occurs for a commercial aircraft in a landing configuration, recovery is practically impossible unless the roughening elements are removed (e.g., the aircraft exits the rain). The lift penalty at low angles of attack was not assessed in the Haines and Luers study but, based on other type roughness studies,[2] is expected to be on the order of 10%. The roughened airfoil study consisted of a theoretical analysis which at this time lacks confirming experimental measurements. It has, however, been established by wind tunnel measurements[2-4] that fixed roughness elements such as those associated with a contaminated or frosted airfoil do produce the magnitude of drag and lift penalties indicated above and that these penalties occur on airfoils both with and without high lift devices. Thus the referenced study applies the known results concerning fixed roughness elements on a wing to the situation of rain producing these roughness elements.

To qualitatively test the conjecture that heavy rain had a significant influence on several recent aircraft accidents attributed to windshear, an analysis of two aircraft accidents was undertaken. In each of these accidents the aircraft was embedded in a heavy rain cell at or near the instant when the performance degradation occurred. The accidents/incidents studied were the Eastern Airlines Flight 066 accident, JFK International Airport, in June of 1975, and the Eastern Airlines Flight 693 incident, Atlanta, Ga., in August 1979. The primary document upon which the analysis of each accident was based was the National Transportation Safety Board's (NTSB) aircraft accident report. In each accident/incident the NTSB reconstruction of the aircraft flight trajectory produced a probable profile of horizontal and vertical windshear that the aircraft encountered. In deriving these profiles the NTSB assumed that the only external factor acting upon the aircraft was the wind. If another factor produced aerodynamic penalties, such as heavy rain, the derived wind profiles would be overestimated by the relative magnitude of the rain-induced penalties. Thus it is probable that if large rain penalties were present, a gross overestimation of windshear was made in the accident investigation. In our analysis, the rain influence was assessed using a fixed stick digital landing simulation program.[5] Drag penalties were introduced into the program by changing the drag coefficient of the aircraft by an amount appropriate for the estimated rainfall rate. The momentum penalty was introduced by the addition of another force term in the equations of motion. Lift penalties were not introduced into the landing simulation program because the referenced study only assessed decreases in maximum lift. Thus at low angles of attack, changes in lift coefficient were not available.

Eastern Boeing 727-225 Accident, JFK, 1975—NTSB Analysis

On June 24, 1975, Eastern Airlines Flight 066, a Boeing 727-225 aircraft, crashed into the approach lights to Runway 22L at JFK International Airport, Jamaica, N.Y. The aircraft

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was on an ILS approach to the runway through a very strong thunderstorm that was located astride the ILS localizer course. The NTSB determined that the probable cause of this accident was the aircraft's encounter with adverse winds associated with the very strong thunderstorm which resulted into a high descent rate into the nonfrangible approach light towers. According to the NTSB report[6] the adverse winds might have been too severe for a successful approach and landing even had the crew relied upon or responded rapidly to the indications of the flight instruments.

Meteorological Conditions

Witnesses near the middle marker for Runway 22L saw the aircraft at a low altitude and in heavy rain. Five witnesses described the weather conditions when Eastern 066 passed overhead as follows. Heavy rain was falling, there was lightning and thunder, and the wind was blowing hard from directions ranging from north through east. Persons driving on Rockaway Boulevard stated that a driving rainstorm was in progress when they saw the aircraft hit the approach light towers and skid to a stop on the boulevard. Persons in the north and northwest areas of the airport at the time of the accident scene stated that heavy rain was falling. The cockpit voice recorder (CVR) indicates the windshield wipers were turned on at approximately 700 ft and placed on high speed when the aircraft descended to 500 ft. The CVR verified the presence of heavy precipitation. Radar observations near the time of the accident indicated that cloud top heights ranged from 49,000 to 53,000 ft. Rainfall rates associated with a 50,000-ft cloud top height can be estimated from Zawadzki and Ro[7] as a 185 mm/h average over a 5-min period. In the regions of the cell with the most intense rain penetrated by the aircraft over a 20-30-s time interval, a 300-mm/h rainfall rate might or could be expected. According to Ref. 1, significant drag, lift, and momentum penalties would be associated with this rainfall rate. The drag penalty is estimated to be in the range of from 10 to 15%. The momentum loss was estimated by scaling the 747 results (from Ref. 1) to a 727 size aircraft. Though some lift penalty at low angles of attack probably occurred, its magnitude was unavailable for use in this analysis.

UDRI Analysis

Fixed stick digital landing simulations were performed to estimate the contribution that drag and momentum penalties associated with heavy rain may have made. Figure 1 shows a fixed stick landing simulation for a 727 aircraft trimmed to the glide slope at 500 ft. Trajectory A is the trajectory that the aircraft would have taken with no additional pilot input and with the aircraft influenced only by the vertical and horizontal windfield derived in the accident reconstruction. For comparison purposes, this will be called the crash trajectory even though it only represents the trajectory the aircraft would have taken had there been no pilot response. To assess how much the windshear profiles could have been influenced by rain penalties, yet provide the crash trajectory, curves B and C were generated. Curve B is that trajectory resulting from a combined heavy rain drag penalty of 12%, a momentum penalty for 300-mm/h rainrate and windshear values of 50% of those calculated in the accident reconstruction. Curve C results from 50% wind shear values with no rain penalties. Note that in these fixed stick simulations the crash trajectory can be effectively reproduced with only half the original magnitude of the wind if rain is also taken into account. Thus we conclude that the derived Eastern 066 wind profiles could have been overestimated by a factor of 2.

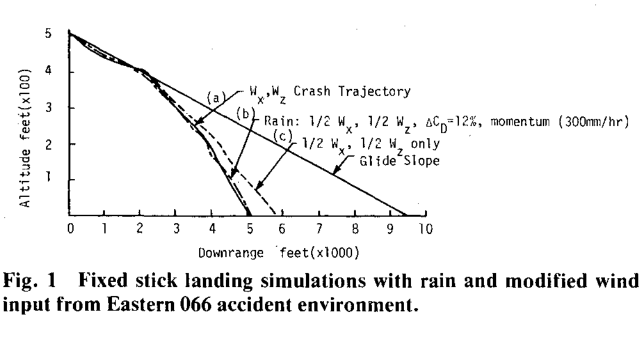

Fig. 1 Fixed stick landing simulations with rain and modified wind input from Eastern 066 accident environment.

B-727 Incident at Atlanta, Ga., August 22, 1979—NTSB Analysis

According to the NTSB Aircraft Incident Report,[8] "On August 22, 1979, Eastern Airlines, Inc., Flight 693, a Boeing 727-25, encountered a small but intense rainshower with associated wind shears on the final approach to the William B. Hartsfield Atlanta International Airport, Atlanta, Ga. The aircraft, with 71 passengers and 6 crew members onboard, came within 375 ft of crashing before it exited the shower and a missed approach was completed."

According to the flight crews, the aircraft was flying in light rain until at about 1000 ft above ground level the rain and turbulence increased. The rain became heavy and according to the flight engineer it was heavy enough to increase the noise level within the cockpit. Ground visibility was lost and was not regained until after the aircraft flew out of the rain. According to the crew, at about 1000 ft, simultaneous with the increased levels of rain, the indicated airspeed began to fluctuate. It decreased from 135 knots to about 120 knots, increased to about 140 knots, and a few seconds later decreased to 108-110 knots. The rate of descent increased to 1000 ft/min. At 800 ft the first officer, who was flying the aircraft, rotated the aircraft to 10 deg nose-up pitch attitude, advanced the thrust lever, called for takeoff power, and began execution of a missed approach. According to the first officer, the pitch correction and added thrust had no effect, the descent rate increased to 1500 ft/min and then to 2100 ft/min. He then rotated the aircraft to 15 deg nose-up and advanced the thrust levers to their forward stops. At from 500 to 600 ft above the ground and at an airspeed of about 110 knots, the stall warning systems stick shaker activated. According to the captain, he estimated the stall warning system operated for from about 10 to 20 s. The first officer then said he reduced the nose pitch angle from 15 to 12 deg and the stick shaker stopped shortly thereafter. According to the flight crew, the aircraft flew out of the precipitation at 375 ft in a right-wing-down attitude and began to accelerate. The descent rate was arrested and a climb began.

According to the NTSB report,[8] "Comparison of the flight data recorder (FDR) data to the predicted performance capability of the aircraft indicated that at 28-s FDR foil time the aircraft encountered either an increasing headwind or a decreasing tailwind; about 104-s FDR foil time, the aircraft encountered a combined change in horizontal wind velocity and a downdraft that ranged in magnitude from 2000 to about 3000 ft/min; and between 120 and 128 s the aircraft's erratic acceleration and deceleration were probably caused by a sudden headwind shear. However, by 130 s, the aircraft's performance was consistent with predicted capability."

UDRI Analysis

For the Atlanta incident, cockpit visibility lowered such that at 1000 ft and below, visual contact with the ground was lost. It was not regained until the shower was exited at 375 ft altitude. According to an experimental study by Bartishvilli[9] of visibility in heavy rain, a 400-mm/h rainrate is required to produce a 1000-ft visibility. A visibility of 375 ft requires a rate greater than 1500 mm/h. Of course, the film on the windshield probably complicates the visibility issue such that a lighter rainfall rate than mentioned here would produce the reduced visibility. For our analysis we estimate the aircraft experienced a rainrate of 300 mm/h between 1000 and 375 ft.

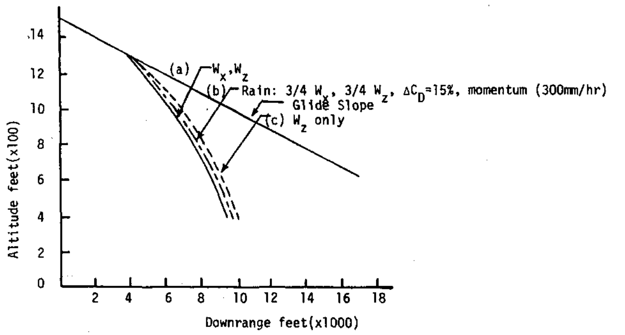

Fig. 2 Fixed stick landing simulations with wind and rain inputs from Eastern 693 incidents.

In our study, the vertical and horizontal wind profiles derived from the NTSB analysis and the time of the heavy rain encounter were used in a simulation analysis similar to that performed for the Kennedy crash. Figure 2 shows the resultant fixed stick trajectories. Note that in this incident, nearly the entire glide slope deviation must be attributed to the vertical windshear, curve C, as compared to curve A. This result would tend to rule out any engine underperformance due to ingestion of large amounts of water, since engine underperformance would largely be reflected in airspeed loss and thus be interpreted as a horizontal wind. Curve B was derived by introducing into the simulation a rain-induced momentum penalty for 300-mm/h rainrate and a drag penalty of $\Delta C_D = 15\%$ as well as horizontal and vertical wind components that were 75% of those derived in the accident investigation. Note that by taking the rain-induced drag and momentum into account, over 75% of the windshear is still required to approximate the windshear trajectory alone. Thus the drag and momentum penalties associated with the rain were not a primary factor in this analysis.

The vertical windshear profile, derived from the accident investigation was of extreme intensity—from 33 to 50 ft/s. The question arises whether the lift penalty associated with rain-induced roughness at a high angle of attack may have been a factor and if this factor could have resulted in an overestimation of the vertical wind component. According to the flight crew, at 800 ft the aircraft was rotated to a 10-15-deg nose-up pitch attitude during its encounter with heavy rain. With 10-deg nose-up and a vertical descent rate of 2000 ft/min in still air, an 18-deg angle of attack, sufficient to activate the stick shaker, would result. The rain-roughened airfoil at this angle of attack would provide considerably less lift and would stall at several degrees less angle of attack than a smooth airfoil. In fact, when the stick shaker activated it is likely the aircraft was already in a stalled configuration. If this were the case, the decreased lift rather than the extreme downburst may have been the cause of the aircraft's rapid loss in altitude. With a reference speed of $V_{\text{ref}} = 120$ knots (Ref. 8) and a customary 30% stall margin, the calculated clean wing stall speed is 92 knots. The amount of loss in maximum lift necessary for the aircraft to stall at 110 knots, derived from relating the lift coefficient to the square of the airspeed, is 30%. Thus a rain induced decrease in maximum lift of 30% would have caused the aircraft to enter a stall at approximately 700 ft. A 30% loss in maximum lift is on the order of that associated with a 300-mm/h rainrate, a rate that is reasonably deduced from the incident description. The recovery from stall we believe occurred because the aircraft exited the rain cell. The airfoil was no longer roughened, and lift was restored. This is consistent with the crew's observation that they flew out of precipitation at 375 ft and began the recovery. Other events concerning this incident also tend to support the heavy rain theory over that of an immense downdraft at such a low altitude.

One such event is the activation of the stick shaker. If it were a large downdraft that caused the aircraft to continue to descend, even with takeoff thrust and at a high angle of attack, then the climb performance capability of the aircraft would indicate that the aircraft should have been climbing with respect to the descending air mass. This implies that the aircraft's angle of attack would have been less than its pitch angle. With pitch angles on the order of from 10 to 15 deg, the resulting angle of attack should have been on the order of 5 deg. This would preclude the activation of the stall warning system which is based on an angle of attack measurement. Thus we believe that it is a contradiction that a large downdraft could have existed simultaneously with activation of the stall warning device.

The heavy rain conjecture also does not require the existence of the small-scale downburst event, which endured only a matter of minutes and was not observed by aircraft closely preceding or following the affected aircraft.[8] It also was not observed by any ground measurement sensors, and did not activate the low level windshear alert system in operation at the Atlanta airport at the time of the incident.

The heavy rain conjecture presents an explanation of the incident that is consistent with the meteorological situation.

Other Heavy Rain Accidents

The two accidents/incidents cited are not believed to be the only ones involving heavy rain. In a review of large fixed-wing aircraft accidents between 1964 and 1975, Shrager[10] identified 25 accidents in which the presence of low-level windshear was a distinct possibility. Of these 25 accidents, precipitation, either rain or snow, was reported in every case. In 17 of the accidents, moderate to heavy rain showers were present along the aircraft's flight path. In 13 cases, a thunderstorm squall was within 5 n.mi. of the runway along the aircraft's flight path. Of these 13 accidents, 12 aircraft experienced moderate to heavy rain along the flight path. Though not all of these accident briefs have been analyzed in our study, several have. The following are some excerpts of interest

Flying Tiger DC-8, Okinawa, Ryukyu Islands, July 27, 1970

"Ground witnesses reported that just north of the approach end of the runway there was a heavy rain shower from which the aircraft emerged at very low altitude just before it struck the water."[11]

Ozark Fairchild Hitler FH-227B, St. Louis, Mo., July 23, 1973

"At 1742:31 the local controller said, 'Ozark eight-oh-nine, it looks like a heavy rain shower moving right across the approach end of the runway now.' The first officer replied, 'Roger, we see it.' That was the last transmission from the flight. The CVR stopped at 1743:24."[12]

Delta DC-9, Chattanooga, Tenn., November 27, 1973

"This occurred (excessive rate of descent) despite two verbal reports of increasing sink rate by the first officer. The captain disregarded the report of the first officer, possibly because of the influence of a visual illusion caused by the refraction of light through the heavy rain on the windshield."[13]

Eastern B727, Raleigh, N.C., November 12, 1975

"...he lost all forward visibility as the windshield became 'opaque' and the external light glare became 'brilliant.' He (the Captain) described the situation as encountering 'a wall of water' and as having 'the bottom fall out' as he added thrust."[14]

Allegheny DC-9, Philadelphia, Pa., June 23, 1976

"Its captain (another air carrier holding on the taxiway) said that the rain was heavy and that he first saw Flight 121 when the aircraft emerged from the rain at 75 to 125 ft above the ground. He further stated that Flight 121 appeared to *stop flying*, descended to the ground with nose-up....''[15]

Jordanian B-727, Doha, Qatar, March 13, 1979

"Prior to and at the time the accident occurred the rainfall was recorded as 'violent'...it was the worst storm they had ever seen on the ground.''[16]

Pan American B-707, Pago Pago, January 30, 1974

"Several persons, who were waiting at the airport terminal for Flight 806, stated that it was raining heavily when they saw a glow near the approach end of Runway 5, which later proved to be the burning aircraft.''[17]

In each of these accident investigations, any aerodynamic performance penalties due to the rain factor were not taken into account. We believe that in each of these accidents, as well as many others, lift, drag, and momentum penalties were a serious contributor to the accidents and in several situations may have been the primary factor. Further research effort is underway in the quantitative determination of rain influence on these and other aircraft accidents.

Conclusions and Recommendations

An initial evaluation of the aerodynamic effects of heavy rain on two windshear accidents, based upon the theoretical results of Ref. 1, indicates that heavy rain may have been a significant contributor. Two types of landing accident scenarios appear evident. In the case of aircraft (shortfall) touchdown prior to the runway, drag and momentum penalties appear predominant. The increased drag due to surface roughness and the momentum loss due to raindrop impacts tend to slow the aircraft and make it descend below the glide slope. A small lift loss at low angles of attack would also tend to increase its descent rate, making it prone to a premature touchdown. A second type of landing accident scenario results when an aircraft attempts a go-around in the heavy rain environment. Accidents/incidents, such as Atlanta 1979, Philadelphia 1976, and Qatar 1979, exhibit situations in which the aircraft, while attempting to climb at a high angle of attack, rapidly lost airspeed, which ultimately degenerated into a very rapid descent rate. In this situation, we believe the drag and momentum penalties for a climbing aircraft with higher exposure rate to raindrop impacts produce an even more serious loss in airspeed until in some cases (accidents) the airspeed approaches stall and, perhaps, activates the stick shaker. With the roughened airfoil, the aircraft may stall even before the stick shaker activates because of the roughness-induced decrease in stall angle. Thus the pilot has no warning of an approaching stall.

The possibility that rain is a factor in thunderstorm related "windshear" accidents has far-reaching implications. Since, with one exception, in each likely thunderstorm windshear accident reviewed by Schrager, the aircraft was exposed to moderate to heavy rain along the glide path gives credence to one of two possibilities: either the rain produced the serious aerodynamic penalties or the severe windshear penalties occurred in the region of heavy rain. This latter possibility is in disagreement with recent Doppler radar measurements of thunderstorm cells by Zrnic and Lee,[18] who concluded that the region of maximum windshear is often not the region of heaviest precipitation. Nevertheless, in either case, avoidance of the heavy rain cell is a desirable criterion to provide a safe landing condition. Since the observation of regions of heavy rain is relatively simple, as compared to windshear observations, it is recommended that primary emphasis by pilots and tower controllers be placed upon the avoidance of heavy rain cells on final approach and on takeoff climbout.

From a safety viewpoint, the most serious encounter with rain would be expected to occur in the landing, takeoff, and go-around configurations. In these configurations, air speed is slow, stall margin minimal, and rain effects are maximum. The reason rain effects are maximum is because, in these configurations, the aircraft has leading edge slats deployed and is intercepting considerably more water drops than at cruise configuration with retracted high lift devices. Furthermore, the extended leading edge slats present a leading edge orientation nearly perpendicular to the direction of the incoming rain. Thus a high collection efficiency is expected to occur near the leading edge, which is known to be the region of the airfoil most susceptible to roughness elements. Thus it appears plausible that an aircraft may penetrate a heavy rain cell, at altitude, in a cruise configuration, with minor aerodynamic penalties relative to what would be experienced by the same aircraft penetrating the same rain cell while landing. For the takeoff or go-around maneuvers, similarly severe rain-induced aerodynamic penalties would be expected as well as the additional problems associated with the aircraft being at a high angle of attack, with a larger presented area to the rain.

Though the results generated in this Note and the accompanying article are not experimentally validated and, perhaps will not be immediately because of the difficulties involved in experimentally simulating very heavy rain, the problem is of sufficient concern and importance to require a careful reassessment of procedures.

The following suggestions are offered. No aircraft should penetrate heavy rain cells while in a landing, takeoff, or go-around configuration. All pilots should be alerted to the possibility of a significant increase in descent rate and decrease in airspeed when penetrating a heavy rain cell. Pilots should be alerted to the fact that an aircraft may stall at an airspeed considerably above the calculated stall speed if roughness elements are present on the wing. In addition, all pilots should be aware of the possibility that an aircraft may stall prior to activation of the stall warning stick shaker. Finally, if execution of a go-around in heavy rain is necessary, high angle of attack, and rapid climb go-arounds that result in a bleeding of airspeed should be avoided. Rather, an increase in airspeed with slower climbout to assure an adequate roughened wing stall margin is suggested. It should be noted that this suggestion is in opposition to recommended procedures for an aircraft exposure to windshear[8,19,20] where a rotation to a high angle of attack is recommended until the descent rate is arrested. Our results suggest that the windshear procedure may be very unwise for encounters with heavy rain and in fact could lead to an accident.

Acknowledgments

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Effect of Swirl on the Potential Core in Two-Dimensional Ejector Nozzles

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Introduction

IN the past, ejector nozzles were used to pump cooling air and to enhance engine thrust. A number of studies were made to investigate the pumping and performance characteristics of the axisymmetric ejector nozzles (see, for instance, Refs. 1-3). With the increasing emphasis on two-dimensional (2-D) nozzles, it now becomes appropriate to study the 2-D ejector nozzles. The two-dimensional version of the ejector nozzles enables the designer to reduce the mixing shroud length to save weight and still achieve sufficient primary plume entrainment and sufficient mixing between the primary and secondary streams. Since engine swirl enhances 2-D nozzle plume entrainment and mixing,[4] it is expected that swirl can further reduce the length of a 2-D ejector nozzle. Hence a semiempirical method for considering the swirl effect was derived to predict the potential core length of the 2-D primary nozzle. Preliminary water tunnel tests of a 2-D ejector nozzle model with and without swirl were also conducted to study the effects of swirl. The results are summarized in this Note to show that the combination of swirl and 2-D geometry can dramatically reduce the primary-nozzle potential core and hence the mixing shroud length. The information contained in this Note is useful for such applications as jet noise reduction.

The Model

A plexiglass model of a 2-D ejector nozzle is shown schematically in Fig. 1. The circular inlet duct transforms into a 2-D primary nozzle with an exit aspect ratio of 4. Plastic pinwheels with blade angles of 7.5, 15, and 22.5 deg are inserted in the circular duct as swirl vanes. A rectangular plexiglass duct is attached to the primary nozzle to form a mixing shroud.

Potential Core Length Prediction

Figure 2 is a sketch of a jet issuing from a 2-D primary nozzle with exit height d (the shorter side of the rectangular exit). The exit velocity is assumed to be uniform. The velocity V or V_c is the difference between the local jet velocity and the velocity at the edge of the jet (the secondary flow velocity).

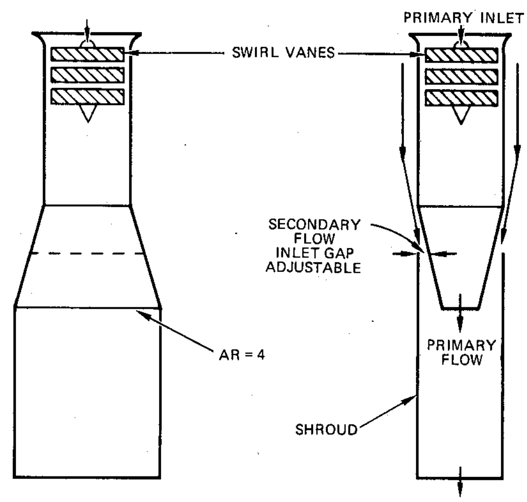

Fig. 1 Schematic of 2-D ejector nozzle model.

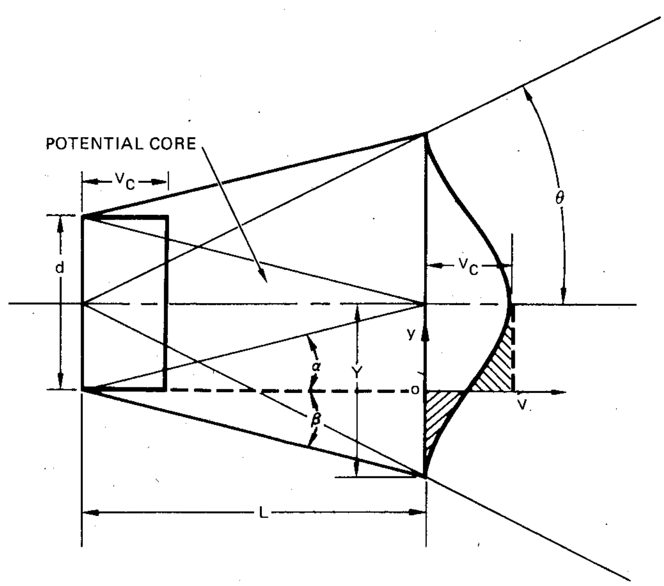

Fig. 2 Structure of jet from 2-D primary nozzle.

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