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Abstract

It is desired to simulate natural rain in a wind tunnel in order to investigate its influence on the aerodynamic characteristics of aircraft. Rain simulation nozzles have been developed and tested at JPL. Pulsed laser sheet illumination is used to photograph the droplets in the moving airstream. Digital image processing techniques are applied to these photographs for calculation of rain statistics to evaluate the performance of the nozzles. It is found that fixed hypodermic type nozzles inject too much water to simulate natural rain conditions. A modification uses two aerodynamic spinners to flex a tube in a pseudo-random fashion to distribute the water over a larger area.

Introduction

This paper will discuss techniques that have been developed at JPL to simulate rain in a wind tunnel and measure its characteristics using photographic methods aided by digital image processing.

NASA Langley Research Center in collaboration with Goddard Space Flight Center-Wallops Flight Facility is currently studying the effects of heavy rain on the aerodynamics of transport type aircraft. Increased drag and a reduction in the maximum lift coefficient have been attributed to surface roughness associated with the water film and to interactions between the droplet impacts and the boundary layer on the surface.[1,2] The regime of greatest interest corresponds to conditions encountered during takeoff and landing. During these phases, the airspeed is low and the aircraft is therefore more susceptible to adverse effects associated with heavy rain.

Rain Simulation in Wind Tunnels

In simulating natural rain conditions in a wind tunnel, it is important to reproduce the correct rain drop size distribution and liquid water content (LWC), defined as the mass of liquid contained in a unit volume of air. As the severity of the rainfall increases, the average drop size increases, as indicated in Fig. 1 and Table 1.[3] Even for very intense rainfall, the drop size will not exceed about 8 mm since larger drops have terminal velocities large enough that aerodynamic forces cause the drops to break up. When water is ejected from a tube, the cylinder of extruded water pinches of into droplets due to surface tension effects. This is known as the Rayleigh instability. The droplets formed in this manner have a diameter very close to twice the internal diameter of the tube employed. If the water injection velocity is sufficiently different from that of the co-flowing airstream, then the droplets will shatter due to the aerodynamic break-up mentioned above.

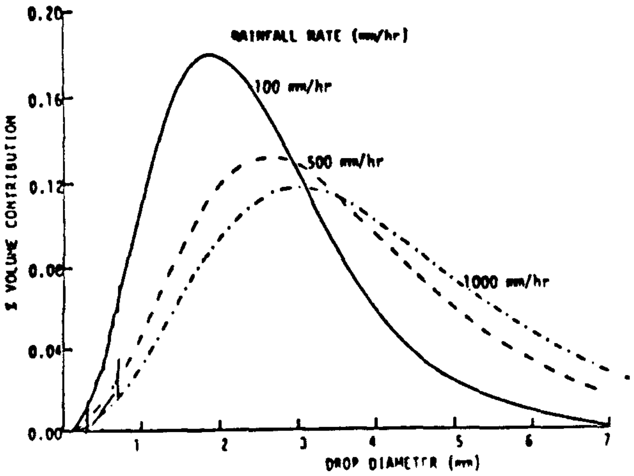

Figure 1. Drop Size Distribution for Natural Rain

Table 1
Natural Rain Intensity Definitions[3]

Classification	Precipitation Intensity (mm/hr)	Droplet Diam. (mm)	LWC (g/m^3)
Fog	Trace	0.01	0.006
Mist	0.05	0.10	0.06
Drizzle	0.25	0.20	0.09
Light Rain	1.0	0.45	0.14
Moderate Rain	4.0	1.0	0.28
Heavy Rain	15.0	1.5	0.83
Excessive Rain	40.0	2.1	1.85
Cloudburst	100 to 1000	3.0	4 to 35

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In the first phase of this project, a set of nozzles, each having several fixed hypodermic needles, was employed to generate water spray in the NASA Langley 4m x 7m wind tunnel. Prior to the Langley tests, the characteristics of these nozzles were evaluated in a small wind tunnel at JPL.[4] An agricultural spray nozzle, which produced a hollow elliptic water spray was also evaluated. The water pressure in this initial series of tests was limited to 100 psi due to safety considerations at Langley Research Center. This pressure restriction resulted in injection velocities low enough that aerodynamic break-up reduced the drop size significantly. If the pressure is increased to match the velocity of the droplets to that of the co-flowing freestream of air, then far too much water is injected, resulting in LWCs an order of magnitude greater than occurs naturally, even in torrential downpours. In an attempt to alleviate this problem, a type of rotating nozzle was developed to distribute the water from a single tube over approximately the same area.

A basic restriction on the use of tubes supplied continuously with water is that when the relative velocity between the air and the water droplet exceeds a critical value dependent upon the diameter of the drop. Larger drops break up more readily than smaller drops.[3] Even with the axial velocity matched to that of the freestream, droplets injected at an angle will still experience a relative velocity which, if sufficiently large, will cause break-up. The larger drops that must be generated to simulate very heavy rain can tolerate only very small velocity differences, which limits the angle that the injection tube can be inclined with respect to the freestream. This, in turn, limits the area that can be covered at some downstream test location.

Some technique for interrupting the flow of water while maintaining a high injection velocity is needed. One possibility contemplated is the use of piezoelectric crystals to produce "droplets-on-demand" as in some inkjet printers. Some difficulties associated with such an approach are that very high pressures must be generated in the crystal and that some technique for aiming the output jet must be devised.

Measurement of Simulated Rain Conditions

In order to measure the characteristics of the rain generated by the various nozzles, a droplet illumination and photographic system was developed at JPL and used in tests both at JPL and Langley. The technique uses digital image processing to determine the drop size distribution. A sheet of pulsed laser light is used to illuminate a cross-section in the area of interest. To aid in visualizing the droplets, a small concentration of fluorescent dye, such as Fluorescein or Rhodamine B6, is added to the water injected through the nozzles. Several photographs are then taken from which the characteristics of the rain are determined. These photographs are digitized using a DeAnza IP 5400 system and a PDP 11/34 host computer as a driver. This system has three color 512x512 vidicon arrays with eight bit resolution for each pixel. In order to reduce noise, 64 successive images of each photograph are averaged. The software developed at JPL identifies droplets in the photographs and determines their diameters. A histogram of drop sizes is then calculated and plotted. The spatial distribution could also be investigated, but this would require many more samples to obtain significant statistics. Basically, it is desired to have a uniform spatial distribution. Poor spatial distribution can generally be determined by visual inspection.

Experimental Apparatus

The JPL open return wind tunnel used to develop the rain nozzles has a test section 18"x18" and a top speed of 200 ft/sec. A streamlined strut extending across the test section shrouds the water supply line which feeds the nozzle being tested. The water is contained in a 20 gallon pressure vessel and is driven by high pressure nitrogen at up to 500 psi. A rotameter in the water supply line gives the flowrate from which the injection velocity and LWC can be determined. A schematic of the experimental setup is shown in Fig. 2.

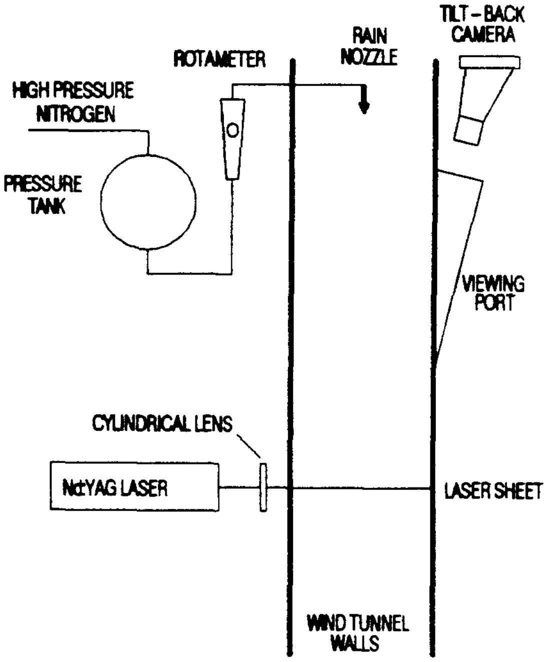

Figure 2. Experimantal Apparatus

The output of a Nd:YAG laser is used to illuminate a cross-section of the flow downstream. The laser provides ten pulses a second, each with an energy of 0.2 Joules and a duration of 20 ns. The beam is passed through a cylindrical lens to form a sheet of light perpendicular to the flow. The thickness of the sheet is equal to the exit diameter of the laser light, about 5 mm.

A tilt-back camera is positioned to photograph the sheet of light. The back of the camera is tilted to keep the film plane parallel to the laser sheet in order to eliminate parallax error. The number of droplets caught in the sheet of light during the pulse is small so typically a multiple exposure is taken of five consecutive flashes. To further reduce errors associated with droplets caught entering or leaving the sheet, a beam expander may be used to increase the thickness of the sheet to about 2 cm before expanding it into a sheet. The image is then digitized and the resulting image is processed using edge detection and thresholding algorithms. Once droplets have been identified, the diameters are determined and a histogram of their sizes is compiled.

Since the resolution of the 4"x5" photographic negative (equivalent to 3350x4200 pixels) is considerably higher than that of the digitizer (512x512 pixels), the image is digitized in several patches to achieve better resolution of the droplets.

Image Processing System

Image acquisition, display and processing is accomplished using a DeAnza IP 5400 image processing system. The hardware package incorporates a vidicon and camera controller for analog image formation, three image refresh random access memory channels, RAM, digital video array processor, and color video display. The analog signal from the video camera is digitized by an A/D converter and fed directly to the array processor which in turn controls the data flow and writes the data into one of the memory planes at a rate of 30 frames per second. The digitization process converts each picture into 512x512 matrix elements (pixels). Each pixel is a one byte number (256 resolution levels) representing the average optical density in an elementary cell whose size determines the spatial resolution of the system. While digitization can proceed at 30 frames per second, 64 consecutive images are averaged to reduce random noise in the vidicon and digitizer. The digitized image is then stored on mass storage devices for further off line processing.

Software residing in the PDP 11/34 host computer operates through a direct memory access (DMA) interface through which the PDP 11 sends and receives information from the video processor registers or from the RAM channels via a driver program. The vidicon image digitization, averaging and storage capability is part of this DMA interface.

To study a droplet picture, the negative is mounted on a flat light table and the vidicon is focused on that plane. Magnification onto the vidicon is adjusted so that the digital resolution is adequate for the smallest drop size of interest. The overall picture is thus composed of a mosaic of subimages. The operator manipulates the light table and vidicon interactively with the computer to follow the desired sampling strategy.

Digital Image Processing Algorithms

Fundamental to the image processing phase of the research is the detection scheme used to identify individual droplets. The main goal is to detect drops with a brightness profile characterized by relatively sharp gradients at the edges and nearly constant brightness values throughout the interior.

A standard approach to dividing an image into two principal brightness values, light and dark, is to select a threshold midway between the two peaks in the intensity histogram. This works well if the areas covered by the two regions are roughly equal. Here, however, the droplets collectively cover a much smaller area than the background and it is difficult to isolate the small hump in the histogram associated with the drops. In a variation of this technique, the intensity histogram is calculated only in regions with gradients above a pre-selected level. Thus, the histogram is composed mainly of points near the droplet boundaries. Typically a value near the single peak of this distribution is used as the discriminator between "dark" and "light" regions of the image. Fig. 3 contains a sample digitized subimage. The regions of this picture with high gradients are depicted in Fig. 4 in white. Based on the intensity histogram for the original image in just these regions, a theshold is selected and applied to the original image. The result is shown in Fig. 5. The area of each droplet is found by counting contiguous dark pixels after holes in droplets have been filled in. The

Figure 3. Original Digitized Sub-image

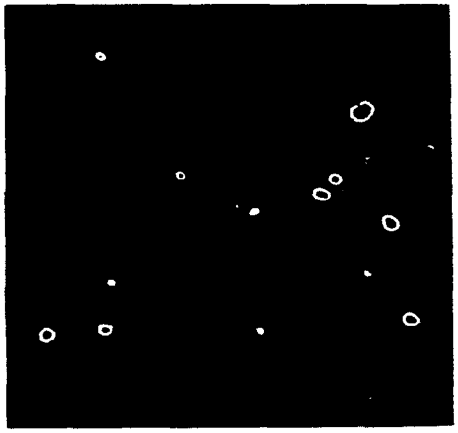

Figure 4. Regions with Large Gradients

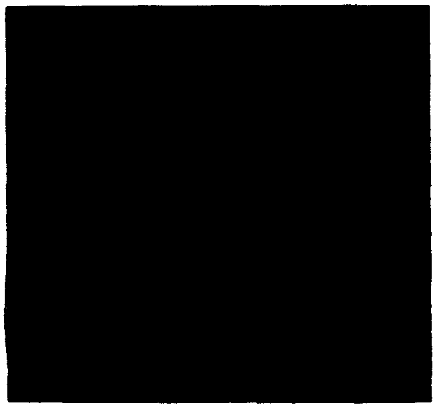

Figure 5. Result of Thresholding

diameter of a circle with the same area is calculated and the droplet statistics based on this parameter are estimated.

Sometimes superimposed droplets are considered as a single droplet by the algorithm. A test compares the actual circumference of a dark region to the circumference of the circle with the same area. Clearly, in all cases, the actual circumference will be greater than or equal to that of the circle. If the ratio of the two exceeds some criterion, then the operator is flagged and give the option of eliminating the offending patch from the calculation of the statistics. The result of this operation is shown in Fig. 6 for the sample mentioned above.

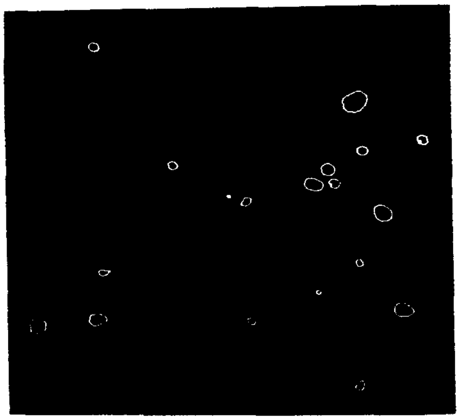

Figure 6. Final Image with Elongated Elements Removed

Earlier work used back-lit droplets to form silhouettes. The depth of field was determined by the camera optics and so a sharpness test was also applied to the digitized images to eliminate out-of-focus drops. In the present work, a sheet of laser light is used and only drops contained within the sheet are illuminated, thus eliminating the problem of out-of-focus drops.

Comparison of Nozzles

Several nozzles were tested during the course of the project. Commercially available nozzles used for crop dusting, etc. generally provide far too much liquid for use in rain simulation.

A family of multitube nozzles, depicted schematically in Fig. 7, produce droplets with diameters about 2 mm, which is reasonable for rain intensities classified as excessive. However, the LWC obtained is about 100 g/m^3, which is too high for any naturally occurring rains.

A type of rotary nozzle was also developed consisting of a stainless steel tube about three inches long with an internal diameter of 0.070". Two counter-rotating aerodynamically driven spinners rotate freely on this tube at slightly different speeds and drive the exit in a pseudo-random pattern, causing the water to be injected at angles up to about 5°. This nozzle is shown in Fig. 8 and produces droplets with diameters of about 1 mm, a little smaller than the multitube nozzles discussed above. Since this strategy uses a single tube to cover an area comparable to that produced by the multitube nozzles, the LWC is reduced considerably. LWC on the order of 20g/m^3 have been obtained, which is within the range described as a cloudburst.

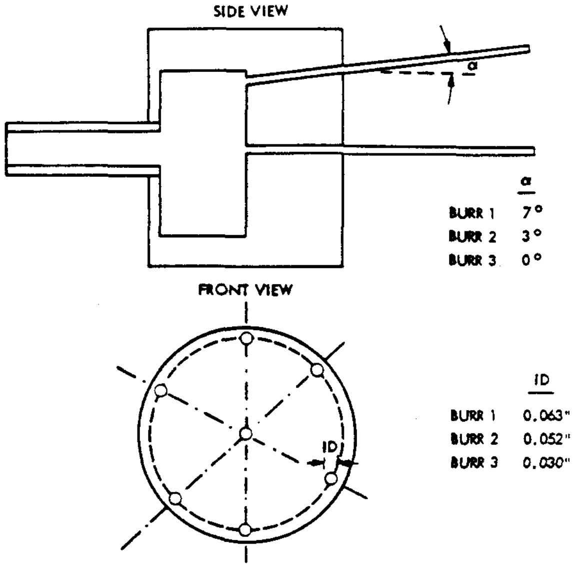

Figure 7. Multitube Nozzle

Figure 8. Nozzle with Double Aerodynamic Spinners

Sample histograms showing the diameter statistics for the rain produced by the BURR1 multitube nozzle and the double spinner nozzle for similar operating conditions are shown in Figs. 9 and 10. It can be seen that the distributions are very similar for the two nozzles.

Concluding Remarks

Several nozzles have been developed to simulate very heavy rain conditions in a wind tunnel. Provided the droplet injection velocity is kept sufficiently close to the airstream velocity the droplets will form with diameters close to twice the internal diameter of the tube. If the two velocities differ significantly then the droplets will break up into smaller drops due to aerodynamic effects.

A nozzle with double aerodynamically driven spinners produces the closest liquid water content (LWC) to values that occur naturally in cloudburst conditions. The spinners cause the tip of the nozzle to follow a pseudo-random pattern to distribute the droplets over a larger area than would be covered by a fixed tube nozzle.

Photographs taken using a pulsed laser sheet to illuminate the simulated rain drops are digitized and processed to calculate the statistics describing the rain.

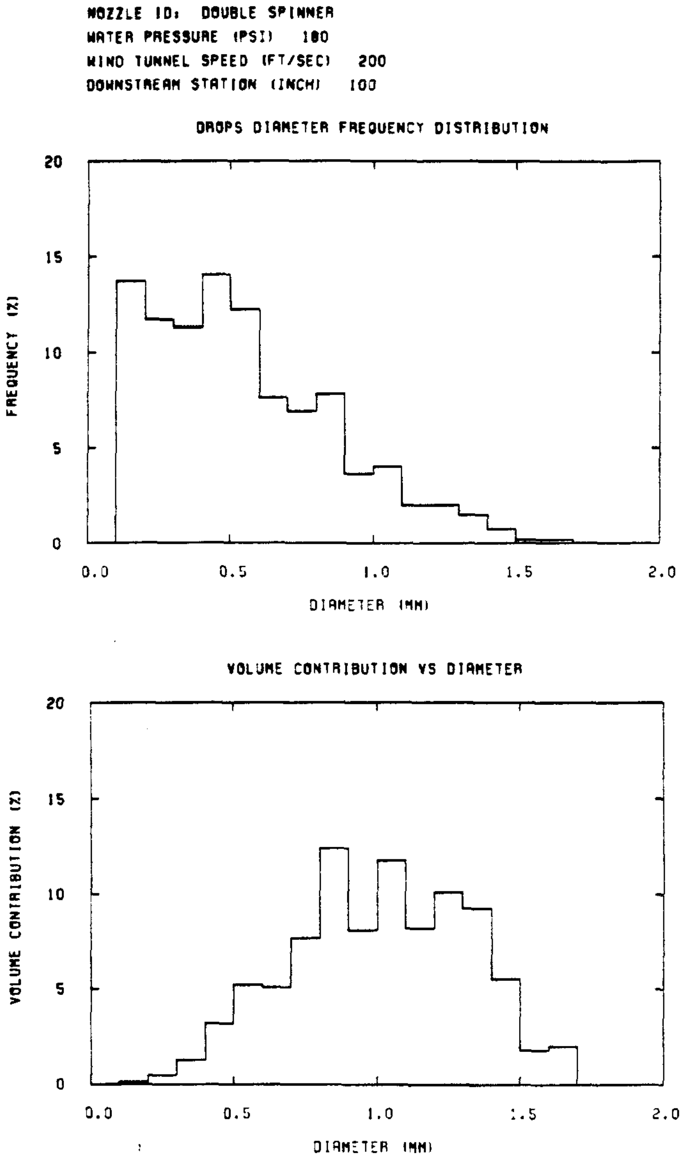

Figure 9. Rain Statistics with Double Spinner Nozzle at 180 psi and 200 ft/sec

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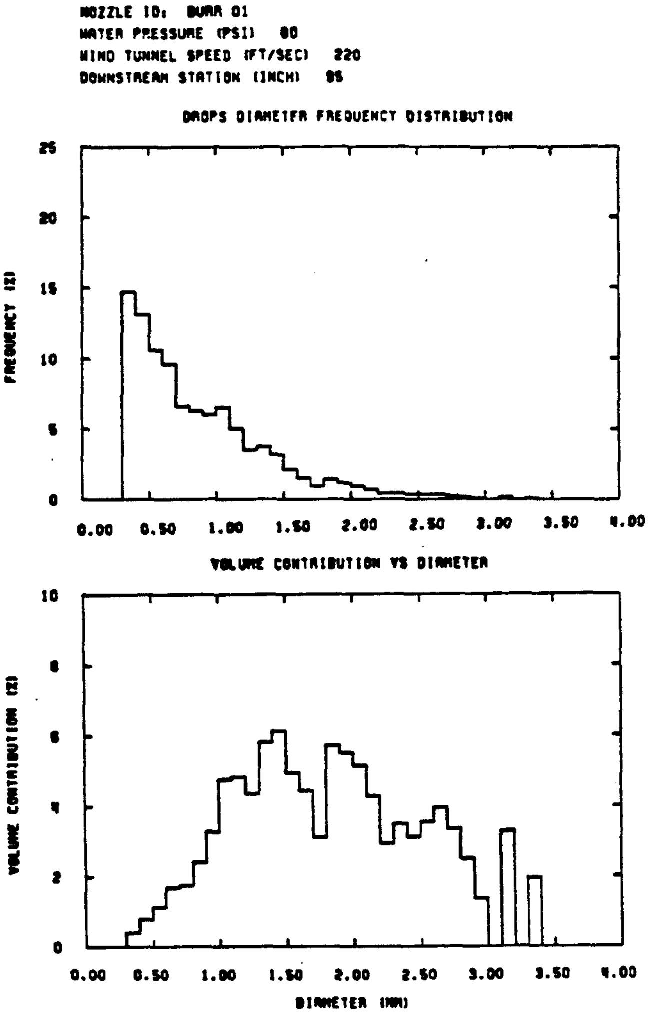

Figure 10. Rain Statistics with Burrl Nozzle at 80 psi and 220 ft/sec

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