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SOME EFFECTS OF RAINFALL ON FLIGHT OF AIRPLANES AND ON INSTRUMENT INDICATIONS

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SUMMARY

Several possible effects of heavy rain on the aerodynamic performance of an airplane and of heavy rain and associated atmospheric phenomena on the indications of flight instruments are briefly considered.

It is concluded that the effects of heavy rain on the performance of an airplane are not so great as to force the airplane down from moderate altitudes. Serious malfunctioning of the air-speed indicator may occur, however, as a result of flooding of the pitot-static head and subsequent accumulation of water in the air-speed pressure line. In strong convective situations, like thunderstorms, the rate-of-climb indicator may also be seriously in error owing to rapid variations of atmospheric pressure when entering and emerging from the convection currents.

INTRODUCTION

As a result of some recent flight experiences under weather conditions in which heavy rainfall was an outstanding characteristic, the question of the effect of such rainfall on the aerodynamic performance of airplanes was raised, particularly with regard to the possibility that an airplane might be forced to earth from moderate altitudes.

When the excessive drag and the low power of older airplanes and the high wing and power loadings of the newer types of airplanes are considered, a little reflection indicates that even heavy rainfall should not increase the drag or the weight of a modern transport airplane sufficiently to force the airplane down or even to interfere seriously with its normal flight. Nevertheless, it is of some interest to consider the question briefly from a quantitative point of view to gain a concept of the order of the reduction in performance and of the behavior of the airplane under certain circumstances. In addition, because the airplane is frequently flown blind or by instrument when heavy rainfall is encountered, any effect the rain might have on the indications of the instruments is of potential importance.

In this paper, several calculated effects of rainfall on the aerodynamic performance and the behavior of a typical transport airplane are presented. The effects of rainfall and of the changes in air density on the airspeed indicator and on some of the other instruments affected by atmospheric conditions are also briefly discussed.

RAIN DENSITY

According to a recent estimate prepared by the U.S. Weather Bureau, the maximum rain density likely to be experienced anywhere in the eastern portion of the United States is about 50 grams of free water per cubic meter of air. This value represents extreme conditions of actual rainfall in a cloudburst, which is the sudden dropping of large quantities of water that have, through devious convection processes, been accumulating in a relatively restricted zone within the storm cloud. Such a rainfall has a very short duration, namely, about 1 minute. A rain density of 50 grams of free water per cubic meter of air is equivalent to a rainfall of about 1.4 inches per minute if the falling velocity is taken as 12 meters per second, which is the sum of an assumed velocity relative to the air of 5 meters per second, and an assumed velocity of the descending air current of 7 meters per second.

In the following analysis, calculations are based on the estimated maximum rain density of 50 grams per cubic meter. Although greater densities within storm clouds are not entirely precluded, it is felt that greater values must be extremely rare and of extremely limited duration or spatial extent. The limited duration of the greater densities has considerable bearing on the problem because the duration at usual flight speeds would have to be of appreciable magnitude to force an airplane down from the ordinary cruising levels even if the forces involved were great. The calculations are further based on an assumed average falling velocity of the rain, relative to air, of 20 feet per second. This value was chosen after examination of figure 1 of reference 1; it is somewhat greater than the Weather Bureau's estimated value of 5 meters per second and is therefore relatively conservative. It should be noted that the falling velocity of the rain relative to the earth is irrelevant because an airplane flying through a descending air current moves with the air, except for disturbances caused by turbulence or by sudden transitions from one current to another.

EFFECTS OF RAINFALL ON AIRPLANE PERFORMANCE

Weight increase from accumulated water.- An airplane flying in rain is subject to an increase in weight caused by the adherence of the water to the various surfaces of the airplane. Visual observation in flight through rain indicates that some water accumulates at certain small regions, that some water adheres in the form of fine drops which are continually being forced back by the friction of the air stream, and that some water adheres in the form of large drops which move very little, if at all. Obviously, water cannot exist in any substantial depth except over limited areas where a balance of aerodynamic and gravitational forces on the water exists because it is either blown off by the air stream or flows off by the action of gravity.

In order to get an idea of the weight increase resulting from adhering water, a sheet of duralumin was weighed dry and after it was dipped in water. The increase in weight per unit area resulting from the adhering water was such that, if the same amount were assumed to adhere to the entire surface of an airplane having a wing loading of 24 pounds per square foot, the weight of the airplane would be increased by only a small fraction of 1 percent. Such an amount would, of course, be negligible.

The weight increase must, in any case, be very small for, even in the inconceivable case of a layer of water one-quarter inch thick over the entire wing, the weight increase would be only about 5 percent.

Virtual weight increase resulting from pressure of falling rain.- Rain consists of a mixture of fine and relatively large drops of water that fall at various velocities dependent upon their size.

The large or heavy drops of such a rain impinge upon the upper surface of an airplane in such a manner that a downward pressure is exerted owing to the change in the vertical momentum of the raindrops. With a rain density of 50 grams per cubic meter (0.003122 lb/cu ft) and a falling velocity of 20 feet per second, there is obtained

$$F = \frac{d(MV)}{dt} = \frac{dM}{dt} V = \frac{0.003122 \times 20}{32.2} \times 20 = 0.0388 \text{ pound per square foot of wing area}$$

This downward force is only 0.2 percent of a wing loading of 24 pounds per square foot. It is therefore negligible.

Drag resulting from impinging rain.- Because of the forward motion of the airplane, raindrops also impinge on the frontal area and give rise to an increase in drag. Because the speed of the airplane is high and the rain pressure varies as the square of the speed, and because the normal drag per unit frontal area is small as compared with the wing loading, it is immediately clear that the drag of the rain may not be negligible. This question must therefore be considered in more detail.

Although it would be possible to make a more refined analysis of the problem, for the present purpose it is sufficient to consider two limiting assumptions:

(1) The rain consists entirely of fine drops with an inertia that is small as compared with the viscous forces exerted by the air. This assumption is equivalent to considering that the weight of rain per unit volume of air adds, in effect, to the air density.

(2) The rain consists entirely of large drops that will not follow the air flow but will impinge directly on the frontal area and will be accelerated to the speed of the airplane.

Obviously, the true condition will lie somewhere between these limits.

For a rain density of 0.003122 pound per cubic foot and the DC-3 airplane cruising at 190 miles per hour, there is obtained:

Assumption (1)

The density of dry air at 5000 feet, standard atmosphere is 0.0659 pound per cubic foot.

The virtual increase in density of the air resulting from the presence of the free water is $\frac{0.003122}{0.0659} = 0.0474\rho_{5000}$ or 4.7 percent. If the slight effect resulting from the change in lift is neglected, the increase in drag with the speed constant is likewise 4.7 percent, an unimportant value.

Assumption (2)

The power required for level flight through rain is

$$P_r = \frac{C_D \rho S_w V^3}{2 \times 550} + \frac{d(MV)}{dt} \frac{S_F V}{550}$$

where S_w is the wing area and S_F is the projected frontal area (220 sq ft for the DC-3 airplane). The second term on the right-hand side of the equation represents the extra power required to overcome the drag of the impinging rain. If, in first approximation, it is assumed that C_D and ρ remain constant as the airplane flies into the rain, it is easy to evaluate the reduction in speed resulting from the drag of the rain at constant power output and also the power absorbed by the rain. By use of only the second term, the dive angle and the vertical velocity can be determined for the case in which the speed and the engine power both remain constant; this case represents the possible result during blind flight if the pilot maintains constant speed.

In air that is free of rain,

$$P_r = \frac{C_D \rho S_w V^3}{2 \times 550} = 0.6 \times 1800, \quad \text{or} \quad 1080 \text{ horsepower}$$

Therefore

$$\frac{C_D \rho S_w}{2} = 0.02735$$

In rain, with the same power output and with $C_{D_P}\rho S_w/2$ remaining constant,

$$V = \sqrt[3]{\frac{1080 \times 550}{0.02735 + \left(\frac{0.003122}{32.2}\right)220}}$$

$$= 230 \text{ feet per second}$$

The reduction in speed is therefore

$$\frac{279 - 230}{279} = 0.176 \quad \text{or 17.6 percent}$$

The power absorbed by the rain is

$$\frac{0.003122 \times 220 \times \overline{230}^3}{32.2 \times 550} = 473 \text{ horsepower}$$

or 26.3 percent of the total available power.

In order to maintain a constant speed of 279 feet per second with a constant engine power, the power required by the rain must be supplied by gravity. Therefore

$$\frac{279\ W \sin \beta}{550} = \frac{0.003122 \times 220 \times \overline{279}^3}{32.2 \times 550}$$

With the weight W assumed to be 24,000 pounds, the dive angle β is 4.0° and the vertical velocity is

$$279 \sin \beta = 19.5 \text{ feet per second}$$

The foregoing results clearly show that, although the effect of the impinging of the heavy rainfall on the frontal area of a modern transport airplane is not negligible, it is unlikely to force an airplane down. As previously pointed out, the results obtained under assumption (2) are conservative because rain does not actually consist entirely of large drops, the momentum of which would be completely arrested in the manner assumed. The power absorbed by the rain, although substantial, is less than the reserve power available. If the reserve power is not drawn upon, the speed is not seriously reduced. Finally, if the pilot maintains constant speed and engine power, the path angle and the rate of descent are not such as to result in serious consequences. The conservative rate of descent calculated, which is equivalent to about 1200 feet per minute, would have to be maintained for over 4 minutes and through a horizontal distance of about 13 miles to bring an airplane, flying at 190 miles per hour, down from a cruising altitude of 5000 feet. Such an extent of the heavy rainfall assumed in these calculations is extremely improbable.

Increase in drag coefficient due to roughening effect of adhering rain.- In the foregoing example the possibility of an increase in the drag coefficient of the airplane arising from disturbances to the air flow caused by adhering rain was not considered. Because of the lack of test data, it is impossible to calculate this effect. Any increase in the drag coefficient resulting from rain, however, is probably small on existing airplanes, as observations of wing surfaces during flight indicate only a slight roughening as compared with the structural roughness of lapped plates, exposed rivet heads, and waves in the skin.

A calculation was made on the rather conservative assumption that water could accumulate on the wing in a manner that would result in a protuberance 0.005c in height and located at 0.05c behind the leading edge, where c is the wing chord. The increase in drag coefficient resulting from such a protuberance is reported in reference 2. The results of the calculation indicated that, with cruising power and speed maintained constant, the DC-3 airplane would descend along a path inclined but 3° to the horizontal and that the vertical velocity would be 15 feet per second.

EFFECTS OF RAINFALL AND ASSOCIATED ATMOSPHERIC PHENOMENA ON INSTRUMENT INDICATIONS

Heavy rainfall, as has been implied herein, is usually encountered by an airplane in flight in convective situations with strong vertical currents and turbulence. It is well known that in rough air some of the instrument indications fluctuate about their mean values, sometimes quite violently. Troublesome as these fluctuations might be to the pilot, they are not of primary concern here, although it is worth noting that the gyro instruments may be thrown out of action entirely and that the fluctuation of all instrument indications may obscure the correct interpretation of the attitude of the airplane, particularly when the attitude has been disturbed as a result of previous reaction to instrument indications that were actually in error.

The effects under consideration are actual errors or essentially false indications having their origin in atmospheric conditions directly or indirectly associated with rainfall.

Effect of change of atmospheric pressure and density at constant altitude.- Although not directly related to rainfall, a question has been raised concerning the possible effects on instrument indications of changes in air density at the same altitude within thunderstorms. If such changes exist, the readings of the air-speed indicator, the altimeter, and the rate-of-climb indicator could be affected by them.

As far as the author has been able to determine, neither pressure nor density measurements within convection currents have been made relative to similar measurements outside them at the same absolute altitude; nor, apparently, are these quantities amenable to calculation because of the numerous variables of unknown magnitude that affect the result. That horizontal gradients in both air density and pressure do occur within thunderstorms is hardly open to question, however, for barometric measurements at the ground indicate rapid changes in the pressure of several millibars during the passage of such storms. These changes are caused by the reduced mass of the vertical air column over the storm area resulting from either heating or rotation of the air within the storm or from a combination of the two. The maximum reduction in density and pressure would therefore be expected at ground level but, because of the great height of many thunderstorms, relatively large reductions may also be expected at the usual flying levels.

Although rough calculations indicate that the density changes in thunderstorms are ordinarily of such small magnitude that the air-speed indicator would be affected only to a negligible degree, the pressure changes may be sufficient to cause errors in the altimeter of as much as a few hundred feet. The rate-of-climb indicator may be so greatly in error as to be useless as the apparent changes in altitude may occur within periods of time less than 1 minute, depending on the pressure gradients within the storm and the speed and the direction of flight of the airplane.

Accumulation of rain in air-speed tubes.- Air-speed heads on transport airplanes are frequently located below the nose of the fuselage. Consequently, if rain water can enter and ascend the pressure tubes toward the indicator, an error will result. The question is: Can modern pitot-static heads flood in heavy rain and, if so, can the water rise in either the pressure or the static lines?

In principle, modern air-speed heads are so designed that rain entering the pitot opening impinges on an interior baffle plate, falls to the bottom, and finally drains through any or all of several drain holes. The dynamic pressure is conveyed to the pressure line through an opening in the baffle plate away from the area of impingement, so that water should not enter the pressure line except when supplied in quantities too great for the drain holes to accommodate. Although many variations of the baffling and the drain holes exist in practice, the same basic principle is found in all cases.

It is fairly obvious that an air-speed head will flood if the amount of water supplied to the pitot opening per unit time is greater than the discharge capacity of the useful drain holes at the dynamic pressure corresponding to the speed flown. Since the water supplied is proportional to the rain density and the true air speed and the discharge is theoretically proportional to the air speed, it is evident that there is some critical rain density or a combination of speed and rain density below which the air-speed head remains clear and above which the head becomes flooded.

Before the question of the actual rain density required for flooding is discussed, the probable result of flooding will be considered. Flooding of the head simply means that the baffle-protected opening to the pressure tube is no longer clear of water so that, if a pressure differential exists between the pitot opening and the air-speed indicator, the water will be forced in the direction of low pressure. If this direction is toward the indicator and the indicator is above the air-speed head, water will rise in the pressure line and the air-speed indication will be erroneously low.

There are several ways in which a pressure differential acting toward the indicator will or may develop. The rain impinging on the entrapped water through the pitot opening develops a pressure in the same manner as has been seen in connection with the drag of rain impinging on the frontal area of the airplane. In the case of the air-speed head, however, the pitot opening is so small that it is doubtful whether the rain pressure can properly be considered to be uniform. It seems more likely that there would be a fluctuating pressure ranging from zero between drops to high values when the drops actually impinged. Even so, it is unlikely that the pressure of the rain alone is important. Any head of water rising in the tube would come to equilibrium with the mean rain pressure and the net pressure change at the air-speed indicator would be zero.

More important sources of pressure differential are:

1. A leak in the pressure line

2. Descent of the airplane

3. An increase in the speed of the airplane

If any one or a combination of any of these three situations exists, the entrapped water will be driven up the pressure tube and an error will occur because the only pressure available for balancing the head of water in the tube is the dynamic pressure itself.

The probability of occurrence of such an error, once the head floods, is so great as to be almost a certainty. Slight leaks in pressure tubes, which normally are of no concern, are by no means unusual and might almost be said to be the rule rather than the exception. In the convection currents and the turbulence of cumulo-nimbus clouds, the altitude and the air speed of the airplane are constantly changing as the airplane enters and emerges from the convection currents. An air-speed error is almost bound to occur if the rain density is sufficient to cause flooding of the head.

Now, as far as the question of flooding is concerned, it is possible to calculate the rain density at which flooding will occur if the usually assumed discharge coefficients are taken for the drain holes. Such calculations indicate that modern air-speed heads should not flood with any conceivable rain density. Discharge coefficients of small orifices across which an air stream is blowing at high velocity are highly uncertain and, without a knowledge of the correct discharge coefficients, any calculations that might be made would lead to inconclusive results. Moreover, examination of several supposedly serviceable air-speed heads has disclosed that in some cases the drain holes were clogged; any such head would eventually flood almost regardless of rain density. It was therefore felt that some modern air-speed heads should be subjected to test in simulated rain of various densities and at various air speeds. A brief account of such tests is given in the following section.

TESTS ON PITOT-STATIC HEADS IN SIMULATED HEAVY RAIN

Three modern, electrically heated, air-speed heads were subjected to water sprays at various speeds in the 8-foot high-speed wind tunnel of the NACA laboratories at Langley Field. These heads are designated A, B, and C. They had all been in service but were issued from stock as usable material.

The drain holes of all three heads were completely clogged by foreign matter as received for test. Heads A and B were tested both in the plugged and in the clear condition, while head C was tested only in the clear condition.

The method of testing was somewhat crude and consisted essentially in spraying water on the heads from an ordinary nozzle mounted several feet upstream from the heads. The nozzle was equipped with a diffuser to make the spray as uniform as was practicable, and the spray density was determined from the measured discharge capacity at various valve settings, the spray diameter at the location of the air-speed heads, and the air speed. During a test the air stream was first brought up to test speed, and at a convenient time the water spray was quickly turned on. Flooding of the heads was observed, in the case of heads A and B, by noting the appearance of water in a glass tube mounted in the pressure line immediately above the head and, in the case of head C, by noting the behavior of an air-speed indicator to which the pressure and the static lines were attached. In this last case flooding was presumed to have occurred when the air-speed indicator showed noticeable departures from the previously steady condition. In all cases the time was observed between the moment the water was turned on and the moment flooding was observed.

A summary of the test conditions and results follows:

Head A

[Drain holes clogged; 0.02-inch-diameter leak in pressure tube]

Approximate simulated rainfall (in. per min)	Tunnel speed (mph)	Time to flood (min)
0.8	160	1
Drain holes clear		
.8	160	No flooding in 6
.8	195	Less than 1

Head B

[Drain holes clogged; 0.02-inch-diameter leak in pressure tube]

Approximate simulated rainfall (in. per min)	Tunnel speed (mph)	Time to flood (min)
0.3	160	3
Drain holes clear		
.3	160	No flooding in 6
.3	195	Slightly more than 1

Head C

[Drain hole clear; very small leak, representative of nearly tight installations, simulated by 5-inch length of capillary thermometer tubing]

Approximate simulated rainfall (in. per min)	True tunnel speed (mph)	Remarks
0.20	170	Flooded in 1 or 2 sec; indicated speed dropped 40 mph in 38 sec.
.60	210	Flooded instantly; indicated speed dropped 50 mph in less than 1 min.
.60	190 to 220	Tunnel speed increased from 190 to 220 in 20 sec; indicator showed constant speed.

These test results clearly indicate that modern air-speed heads may flood very quickly when subjected to heavy, but not necessarily extreme, rain densities at the cruising speeds of modern transport airplanes. Head C, which was of an older type than heads A or B, flooded almost instantly under conditions that were rather moderate as compared with the extreme conditions possible.

The behavior of head C was particularly illuminating because it showed that, even with a very small and not unusual leak, the air-speed indication would gradually fall with the actual air speed remaining constant. When the indicated value was held constant, the actual air speed gradually increased. It is obvious that, with a somewhat larger leak, the rate at which the indicated air speed would fall would be greater and vice versa. It would therefore seem that, between the tight condition and the large-leak condition in which large and sudden errors would occur, there is a range of conditions within which serious errors may occur but which are of such a nature as not to be easily recognized. In other words, with a large leak the air-speed indication would quickly drop to very low values so that the malfunctioning of the indicator would be obvious to the pilot, whereas with small leaks or with some of the other causes of the pressure differential acting the behavior of the indicator may be such that the malfunctioning would not be clearly evident. This case is particularly serious because, while flying blind in rough air, the pilot may be led to dive the airplane, in an attempt to maintain constant speed indication, before he recognizes the true situation.

The use of a hand-pressure pump in the pressure line to clear it of water, which is an expedient adopted by some air lines, cannot be considered a guaranty against serious errors if the pilot does not recognize malfunctioning of the air-speed system. A continuously operating mechanical pump, designed to provide a continuous slight flow of air in the pressure line toward the pitot opening ("reverse leak"), has been suggested as an alternative. Tests of a reverse leak, made during the rain tests on pitot tubes previously described in this paper, indicated that the method is successful in principal. Objections have been raised, however, to the use of such a device on the grounds that stoppage of the pressure line by, for example, icing of the air-speed head or freezing of condensed moisture in the line would result in injury to the air-speed indicator. A safer method would be to insure, by proper design and maintenance, that air-speed heads could discharge any amount of water likely to enter the pitot opening. This solution, however, requires further research on the discharge characteristics of small orifices past which air is flowing at high speed and possibly further research on water-trap arrangements within the air-speed head.

CONCLUSIONS

It is concluded that it would be highly unlikely for an airplane to be forced down from moderate altitudes by the deleterious effects of heavy rain on the aerodynamic performance of the airplane.

The effects of rain and the associated atmospheric phenomena on the airplane instruments appear to be of small consequence except in the case of the rate-of-climb indicator and of the air-speed indicator. In strong convective situations the rate-of-climb indication may be so seriously in error as to make the instrument completely useless.

Tests of modern pitot-static heads indicated that they may flood in heavy rain at ordinary cruising speeds. The tests also showed that, under simulated rain conditions, the existence of a leak in the pressure line can cause serious errors in the air-speed indication because of the accumulation of water in the line. Under some circumstances the behavior of the air-speed indicator may be such that existence of error may not be quickly recognized by the pilot.

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