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Effectiveness of Controlled Convection in Producing Precipitation

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The effectiveness of controlled atmospheric convection is analyzed in comparison to natural precipitation at five different locations on the globe. The aerological accelerator, a vertical tube of large height and diameter, presents a method for removal of water vapor from air by vertical convection. The question of whether a period of low precipitation is a period of favorable or unfavorable conditions for production of water by the aerological accelerator is examined. In addition, a prototype of the device is presented, namely, a deep mine shaft that produces water upon condensation in forced vertically rising air.

One of the factors inhibiting the growth of small convective cells in the atmosphere into fully developed thunderstorms is the entrainment of air from adjacent columns into the otherwise buoyant column of air. *Stommel* [1947] first proposed this kind of entrainment in cumulus clouds, and *Squires and Turner* [1962] investigated quantitatively this effect, showing that the entrainment constant α varies inversely with cloud radius.

With the purpose of enhancing the vertical convection and consequent water release, *Starr and Anati* [1971*a*, *b*] and later *Starr et al.* [1972] investigated the possibility of preventing the above-mentioned lateral entrainment by means of a tube of large dimensions within which the updrafts would not suffer the damaging effects of adjacent air columns. The name 'aerological accelerator' was proposed for the device. It works on the principle that there is potential energy in the atmosphere because of a basic unstable lapse rate. Given the proper conditions, this potential energy can be converted by buoyant forces into kinetic energy of vertical motions. Furthermore, such vertical motion of air would cause condensation of water vapor within the air above the pressure level at which the given amount of water vapor saturates the air. The process is self-sustained and needs no external energy, given suitable soundings. All that is required, under favorable atmospheric conditions, is a triggering mechanism, such as a heating of the lower atmosphere by the greenhouse effect induced by solar radiation.

Following the first studies in connection with the operation of the aerological accelerator, a number of interesting questions were raised during discussions with various colleagues. The following point was frequently brought up. The proposed device takes advantage of potential energy of the lower atmosphere due to an unstable lapse rate, and this is the same kind of energy that drives natural convective processes. Is it therefore reasonable to expect that an aerological accelerator will operate poorly during the dry seasons and perhaps produce large amounts of water during the periods when water is abundant in any case by natural processes? Arguments were brought forth, following the same line of reasoning, that a very arid region where water production would be most beneficial would stand little chance to produce any reasonable quantity of water from an aerological accelerator. The validity of these arguments would therefore limit or eliminate the usefulness of the aerological accelerator.

It is the twofold purpose of this short study to examine these arguments and to demonstrate an actual existing prototype of the aerological accelerator. If the reason for the lack of precipitation were merely 'poor storage of energy,' with respect to convection, the objections raised above would be considerably more valid. On many occasions, however, an air parcel happens to be locally stable, although it would reach a level of instability if it were lifted high enough.

The eventual path of the ground level parcel of air (raised first adiabatically and then along a pseudoadiabat) may be compared in this respect to that of a rolling stone placed on the top of a hill. In spite of the fact that ample potential energy is available the stone may be prevented from rolling downward by certain irregularities in the contour of the hill, such as holes and bumps that create locally stable conditions for the stone. The tube of the aerological accelerator smooths the way for the air parcel through inversions, points of stronger lateral entrainment, and other inhibiting factors and is thus analogous to a smooth downhill road paving an easy way for the stone to roll down undisturbed. If these factors are indeed important in preventing convective processes, it is quite possible that during a particularly dry season the potential energy available is ample for convection but cannot spontaneously be released because of various inversions and other such inhibiting factors.

Much benefit is no doubt gained by checking all possible avenues and considering the merits of various speculations. Nevertheless, none of these theoretical considerations can give us the confidence that direct observations are able to give. It was therefore decided to (1) present an existing model that has many similarities to the proposed aerological accelerator and (2) compare conditions for convection in an aerological accelerator with recorded rainfall at several locations: Brownsville, Texas, where a study has already been done [*Starr et al.*, 1972] under natural and artificial conditions; Kingston, Jamaica, where natural orographic conditions are very suitable for high constructions of this kind; Aden, at the southern tip of the Arabian peninsula, one of the most arid locations in the world that has a radiosonde station; Douala, Cameroon, off the Gulf of Guinea, a region of extremely great rainfall at over 4400 mm/yr with an average specific humidity of 18 g/kg at the 1000-mb level; and Karachi, Pakistan, a location with considerable humidity, 16 g/kg on the average at the 1000-mb level, but only about 250-mm annual precipitation.

It is seen that these five places differ considerably from each

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other and cover quite a wide range in the natural conditions domain. A comparison between the rates of production of the aerological accelerator at these locations was thus considered to be very instructive.

COMPARISON

The source of radiosonde data was a set of microcards purchased directly from the World Meteorological Organization center in Geneva. The source of data for precipitation was the World Weather Records, 1951–1960, [*U.S. Department of Commerce*, 1962].

The following equation is used to determine the results at the top surface of the aerological accelerator (see appendix for derivation and symbols):

$$(\langle w_t\rangle^{S_o})^2 = Hg\,\frac{\langle \rho_e - \rho\rangle^V}{\rho_t} - \frac{2H}{\rho_t R}\langle\tau\rangle^S - \langle (w_t')^2\rangle^{S_o}$$

The left-hand term is the advection of vertical momentum across the top by the mean value of the vertical motion. The first two terms on the right-hand side are the gain of momentum due to buoyancy and the loss of momentum due to friction, respectively. The last term on the right is the vertical eddy transport of vertical momentum across the top, which may be disregarded as being much smaller in magnitude than the left-hand term.

Furthermore, it will be assumed that $\langle\tau\rangle^S = C_D\langle\rho w^2\rangle^S$ can be approximated by $C_D\langle\rho\rangle^S(\langle w\rangle^S)^2$, and the following relationship is obtained:

$$\frac{2H}{R\rho_t}C_D\langle\rho\rangle^S(\langle w\rangle^S)^2 + (\langle w_t\rangle^{S_o})^2 = Hg\,\frac{\langle \rho_e - \rho\rangle^V}{\rho_t}$$

The right-hand term of the above is the buoyancy B of a column of unit area, and $\langle\rho\rangle^{S_o}\langle w\rangle^{S_o}$ is the transport of mass T_M in the vertical direction. If we assume that (for considerations of air mass transport only) T_M is constant with height z, then $T_M = \langle\rho_t\rangle^{S_o}\langle w_t\rangle^{S_o} = \langle\rho\rangle^{S_o}\langle w\rangle^{S_o}$. With this approximation and denoting $1/[2HC_D/R\langle\rho\rangle^S + (1/\rho_t)] = \rho^*$, we have

$$(T_M)^2 = B\rho_t\rho^*$$

A computer program was devised that from pressure, temperature, and relative humidity at various levels computes the aerological accelerator outputs in the following order: (1) the densities and density differences (between ambient air and the hypothetical path of the ground air parcel) at the given levels; (2) the densities and density differences averaged for each layer between the levels; (3) the term ρ^*; (4) the buoyancy term B; (5) the vertical mass transport T_M and hence the average vertical velocity; and (6) the maximum possible water production, which is equivalent to T_M multiplied by the mixing ratio of liquid water at the top of the apparatus multiplied by the top surface area.

The results of computations for the calendar year 1958 of a hypothetical aerological accelerator of 50-m radius extending vertically to 700 mb at the five stations considered are

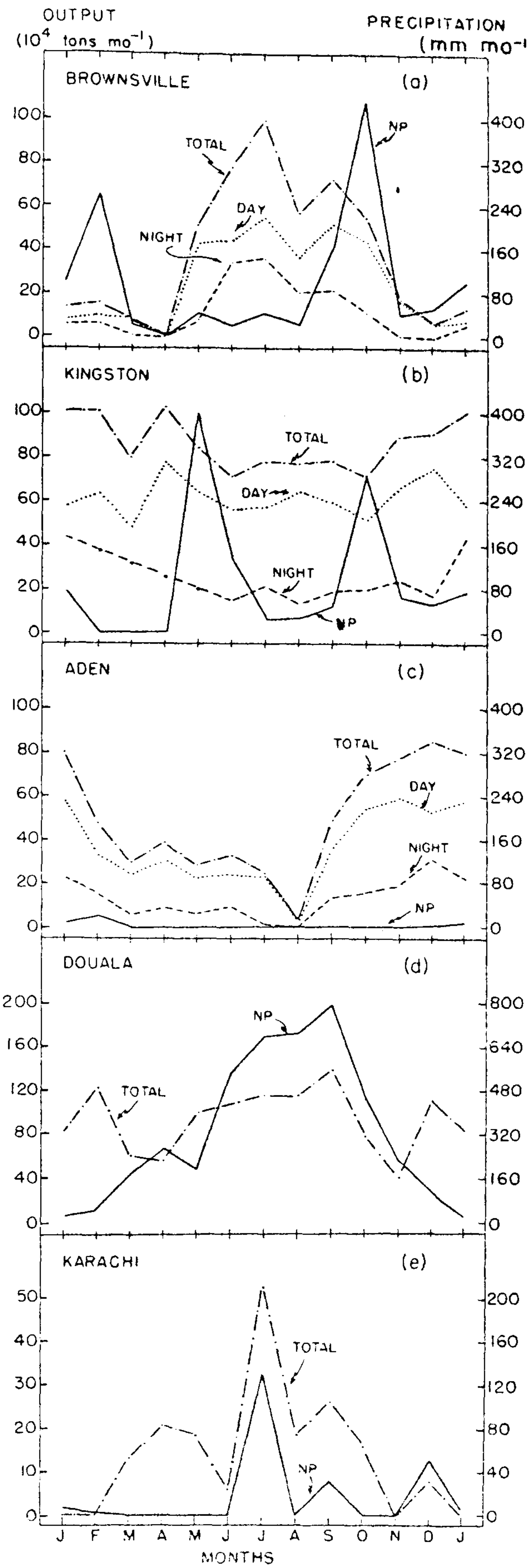

Fig. 1. Natural precipitation (NP) in millimeters per month, daytime aerological accelerator output, nighttime accelerator output, and total accelerator output in units of 10^4 t per month are shown for the calendar year 1958 at (*a*) Brownsville, Texas (station 72250), (*b*) Kingston, Jamaica (station 78397), and (*c*) Aden (station 40597). Natural precipitation (NP) and total accelerator output per month for 1958 are shown for (*d*) Douala, Cameroon (station 64910), and (*e*) Karachi, Pakistan (station 41780).

shown in five graphs in comparison with the natural precipitation at the respective locations (Figure 1). The computations are made with the assumption that no supersaturation occurs and that drops of water, once formed, precipitate downward. Most probably, only part of it will precipitate; a fraction of 50% was considered to be a fairly realistic expectation in a previous publication [*Starr and Anati*, 1971*b*].

Figure 1*a* represents the situation in Brownsville, Texas. Clearly, the main portion of water production occurred in the summer months, a period that does not have large natural precipitation. In the winter (October to March), on the other hand, there seems to be some positive correlation between the aerological accelerator results and natural precipitation.

Figure 1*b* represents the situation in Kingston, Jamaica, again for the calendar year 1958. The correlation, if any, is negative, especially for the second half of the year, where the broad maximum in the aerological accelerator products coincides exactly with the minimum in natural precipitation observed during the months of July, August, and September. Similarly, the sharp minimum in accelerator products, according to the calculations, coincides exactly with the sharp maximum in the natural precipitation recorded for the month of October. This seems to disprove the theory that the two curves should necessarily be positively correlated. Here the seasonal variation is minimal in comparison with that of the natural precipitation. It is worth reminding the reader that by artificially helping the device the seasonal variation can be reduced almost to zero, as was discussed by *Starr et al.* [1972, comment 5].

Figure 1*c* represents the situation in Aden. In this region there is little natural rainfall to speak of, but even here there does not seem to be a positive correlation. Between February and June, if anything, there is a negative correlation between the total accelerator products and natural precipitation. During the 9 months of March to November the total recorded rainfall is only 3 mm, all of which occurs in July and August, and this coincides with the sharp minimum in the aerological accelerator products. Another interesting point is that the accelerator production has a magnitude comparable to that of the other two stations previously examined, whereas the natural precipitation is considerably lower. This questions the objection that arid zones are not suitable for the proposed device. This important point was first observed by *Peixóto* [1971] when, commenting on the article by *Starr and Anati* [1971*b*], he wrote, referring to the apparatus in question: 'The indications are that arid zones are not necessarily unfavorable for the present purpose.'

Figures 1*d* and 1*e* show the natural precipitation and aerological accelerator production of Douala and Karachi, respectively. The aerological accelerator production, however, is based upon one observation per day; for Douala it is at 06 UT (06 LT), and for Karachi it is at 00 UT (05 LT).

In the case of Douala there is a strong peak between July and September of natural rainfall, and aerological accelerator production is just slightly above the rest of the year on the average. In the case of Karachi there is virtually no natural rainfall (less than 10 mm per month) except during the months of July, September, and December. In aerological accelerator production we can observe in this case how the curve follows in excellent correlation during these months. However, there is also some production during March, April, and May, which happens to be the season of lowest rainfall (total for the 3 months is 0.0 mm).

In observing the values of aerological accelerator production in these last two locations in contrast with the others we see that they do not seem to support clearly the previously given arguments with regard to the negative correlation between accelerator production and natural precipitation. We also see how much greater production there is in Douala, where natural precipitation is large, in comparison with that in Karachi. One might conclude also from an analysis of these two stations that a location with favorable conditions for natural convection and hence rainfall will also have, to some extent, good conditions for convection in the accelerator, although this is not always the case. We see from the negative correlations among the first stations that there is still capacity for accelerator production, even during periods of low natural precipitation.

EXISTENT MODEL

Actual prototypes for the aerological accelerator are in existence and described by *Carte* [1968] and *Lambrechts* [1956]. These models are ventilation shafts of very deep gold mines near Johannesburg, South Africa. Although the function of these shafts is to create an upward draft and remove hot moist air from the bottom, an important result was the production of liquid water upon condensation of vertically rising air. The major differences between these shafts and the proposed device are two. (1) The small radius to depth ratio of the shafts creates an enormous amount of friction due to the proportionally large area of the shaft walls. (2) Fans are present that create the updraft and thereby overcome this friction.

Lambrechts noted that this was an actual case of rainmaking by directly removing the moisture from the air. The liquid water so produced was subsequently used for agricultural purposes.

Typical dimensions of an upcast mine shaft are as follows. The depth is approximately 1 km. At the bottom 700 m the shaft has a radius of 3.5 m. For the top 300 m the radius is 3.2 m, and the shaft is constructed of concrete. In such a shaft, water drainage is between 2700 and 4000 l h^{-1}. Carte observes that a single shaft with an airflow of 500 m^3 s^{-1} can produce as much as 4500 l h^{-1} of water.

These shafts produce the same order of magnitude of liquid water per volume as the proposed aerological accelerator does. Table 1 has typical values for the aerological accelerator and ventilation shaft. Here Q is the production of liquid water in metric tons per hour.

A comparison between the water production per volume of each yields the following: the ratio of Q divided by the volume for the aerological accelerator to Q divided by the volume for the ventilation shaft is $\frac{5}{8}$.

We therefore see that water production expected from the aerological accelerator is per volume about the same as water production from these South African mine shafts.

TABLE 1. Typical Values for Dimensions and Rate of Water Production for an Aerological Accelerator and Ventilation Shaft

	Height	Radius	Q
Aerological accelerator	5000	50	2000
Ventilation shaft	1000	3.5	4

The height and radius are given in meters, and Q is given in metric tons per hour.

Discussion

Unfortunately, 4 months of data were mising for Kingston (see Figure 1*b*), for the 12 UT measurements. Since this synoptic hour is the less significant of the 2 hours used, the simplest guess, joining linearly the two nearest available measurements, was adopted with little chance of committing gross errors. The reader should be warned, however, and the following convention was introduced: the four open dots in Figure 1*b* denote the values for the months so deduced.

The units of natural precipitation are not the same as the units for aerological accelerator results. It is therefore necessary to choose an area over which the output from a 50-m-radius accelerator will be spread. Take the density of water as 1 t m^{-3}, and in order to make the resultant curves of similar heights for the sake of comparison the area in question will be chosen to be 2.5×10^6 m^2. We may now compare the annual means. Table 2 shows for the five stations the annual natural precipitation totals, the production for the aerological accelerator, both in tons of water and in millimeters if this water were spread over the above-mentioned area, and the ratio of the accelerator production to natural precipitation. Figure 2 shows this ratio, which is the efficiency of accelerator production plotted versus the natural precipitation. The figure demonstrates that the efficiency of water production is greater in arid regions, whereas a low efficiency exists in rainy regions. This is true because in general we have obtained the same order of magnitude of water production from the accelerator regardless of location, whereas the natural precipitation of the situation was of grossly different magnitudes.

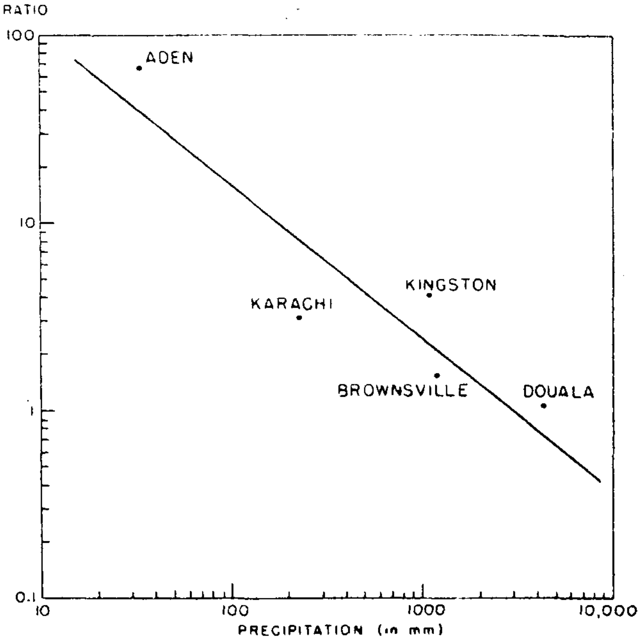

Fig. 2. Efficiency of accelerator (ratio of accelerator production distributed over an area 2.5×10^6 m^2 to natural precipitation) is shown versus the precipitation.

Another point occasionally brought up in discussion is whether a turbine can be operated from the motions within an accelerator. The answer is that this could be, at best, just a minor source of power. Aside from the fact that damping would probably be too great the total power of the ejected air with an average velocity of 10 m s^{-1} would be about 5000 kW, and the efficiency ratio of the turbine would then reduce this value by a considerable factor. However, it is probable that enough power for the operation of various instruments and controlling devices could be supplied if an accelerator were placed in a remote region with no access to power lines.

Although these few examples are not enough for thoroughly meaningful statistical results, the indications of the negative correlation mentioned above at several stations raise some questions. This may be an indication that water resources in lower atmospheric strata are easily exhausted in the process of rainfall, the air at the intake of the accelerator thus being left too poor in moisture to activate the device satisfactorily. Should this somewhat speculative reasoning prove true, we shall face the problem of the reverse process: could a large number of eventual accelerators distributed over the globe have the damaging effect of reducing natural rainfall? The reader will no doubt notice the parallel between this possibility and the damage caused to natural water reservoirs by irrigation and the canalization of water toward other locations, which is another artificial process that started some thousands of years ago.

TABLE 2. Annual Values for Natural Precipitation (NP) and Accelerator Production (AA) at Five Stations

	NP, mm	AA, 10^5 t	AA, mm	Ratio AA/NP
Brownsville	1208	4.595	1838	1.52
Kingston	1088	10.222	4089	3.76
Aden	33	5.653	2261	68.52
Douala	4218	11.363	4547	1.08
Karachi	226	1.826	730	3.23

The AA is given in millimeters if the total water were spread over an area of 2.5×10^5 m^2.

Although they were built for a different function, the presence of condensed water upon upward convection in mine shafts does show that this method indeed has the potential for extracting water from air.

The actual construction of the aerological accelerator is a matter that must be studied with regard to the engineering requirements. These requirements are generally severe, and one may doubt whether they are within the province of present day technology. It is possible that future technology will find solutions to what may be called the problem of proper space platforms within the atmosphere, having useful applications in other subjects as well as in our own.

However, the practical-minded reader may still wish to know how far our current engineering expertise might take us in the actual construction of a device for initial experimentation. It appears that such an experimental model would have to be anchored to a steep mountain slope. At the foot there should be a water surface (possibly artificial) to help furnish moist intake air. The height and diameter of the tube might be reduced considerably if (1) the intake air is near saturation when it enters, perhaps made so by specially designed apparatus, and if (2) there is a means of helping the air to rise inside the tube, perhaps by funneling a sea breeze or trade wind into the intake by proper means.

As is evident, much would depend upon the choice of a favorable site. As a casual thought, one such favorable location within the United States where steep cliffs rise from a moisture-supplying body of water occurs on the northern coast of the island of Molokai in the Hawaiian Islands. At that location there are places at which a 1000-m elevation occurs within only a 600-m horizontal distance. Although water production is not necessarily needed at that location, it might, among possible others, be considered for a pilot project in order to study the technical aspects and to determine whether the natural rainfall can be increased by artificial means with the aid of our device.

The authors consider the study of the aerological accelerator of great interest in its own right, whether or not it appears to be a profitable venture solely for the purpose of obtaining water. The possible use of the device for purposes other than water production, such as air removal for pollution control and heat removal from the surface of a water basin, has been previously discussed [*Starr et al.*, 1972]. Its exploitation for research should be particularly appealing to cloud-seeding groups for purposes of experimentation and observation.

APPENDIX

The set of equations given below relates to the mechanic aspects of the system alone (adapted from *Starr et al.* [1972]). We assume that the mean densities inside and outside our cylindrical tube are given by observation or otherwise known. The symbols to be used are the following.

- C_D coefficient of frictional drag for wall of tube;
- Φ geopotential per unit mass;
- g acceleration of gravity;
- H height of top of tube;
- P pressure;
- P_0 surface pressure;
- P_t pressure at top of tube;
- P_{xz}, P_{yz}, P_{zz} vertical stress components across planes normal to x, y, and z directions, respectively;
- R radius of tube;
- ρ density in volume of integration;
- ρ_e density of environment;
- ρ_0 density at surface;
- ρ_R density at vertical wall of volume of integration;
- ρ_t density at top of tube;
- S area of vertical boundary of V;
- S_0 area of horizontal cross section of V;
- τ frictional stress exerted upward by fluid in V on S;
- u, v, w particle velocities in x, y, and z directions, respectively;
- V volume of cylinder from $z = 0$ to $z = H$;
- v_R outward horizontal velocity normal to wall of volume of integration;
- w_R upward velocity parallel to wall of volume of integration;
- w_0 vertical velocity at surface;
- w_t vertical velocity at top;
- x, y, z Cartesian coordinates with z axis positive upward.

The equation of motion for the vertical direction and the equation for mass continuity may be written in the form

$$\rho \frac{Dw}{Dt} = -\rho \frac{\partial \Phi}{\partial z} + \frac{\partial P_{xz}}{\partial x} + \frac{\partial P_{yz}}{\partial y} + \frac{\partial P_{zz}}{\partial z} \qquad (1)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} \rho u + \frac{\partial}{\partial y} \rho v + \frac{\partial}{\partial z} \rho w = 0 \qquad (2)$$

Making use of (2), we may rewrite (1) as

$$\frac{\partial}{\partial t} \rho w = \frac{\partial}{\partial x} (P_{xz} - \rho w u) + \frac{\partial}{\partial y} (P_{yz} - \rho w v) + \frac{\partial}{\partial z} (P_{zz} - \rho w^2) - g\rho \qquad (3)$$

We now take a volume integral of (3) over V, making use of the divergence theorem. Thus we may write that

$$\frac{d}{dt} \int_V \rho w \, dV = -\int_S \tau \, dS - \int_S \rho_R w_R v_R \, dS + \int_{S_0} (P_0 - P_t) \, dS_0 + \int_{S_0} \rho_0 w_0 w_0 \, dS_0 - \int_{S_0} \rho_t w_t w_t \, dS_0 - g \int_V \rho \, dV \qquad (4)$$

The rate of accumulation of upward momentum in V is given by the right-hand side of (4) with the assumption that $P_{zz} = -P$.

It is now necessary to introduce some assumptions peculiar to our particular problem. These are the following: the conditions are steady with time for integrals in (4); $w_0 = 0$ with sufficient accuracy; $v_R = 0$ except below the lower end of the tube; $w_R = 0$ nearly enough below the lower end of the tube, since the end is near the surface; the environment is essentially at rest and in hydrostatic equilibrium; and P_0 and P_t are the same as they are in the adjacent environment at the same levels. Applying these assumptions, we see that (4) reduces to

$$0 = -\int_S \tau \, dS + \int_{S_0} (P_0 - P_t) \, dS_0 - \int_{S_0} \rho_t w_t w_t \, dS_0 - g \int_V \rho \, dV \qquad (5)$$

If there exists an upward current in the tube, the frictional loss of momentum plus the loss at the top by advection must be made good by an excess of the net pressure force over the weight of the fluid in V, i.e., there must be a buoyancy force acting on the fluid in V.

Let us consider the state of affairs within a corresponding column in the undisturbed environment. We have, in view of our assumptions and using the subscript e to indicate environmental conditions,

$$0 = \int_{S_0} (P_0 - P_t)_e \, dS_0 - g \int_V \rho_e \, dV \qquad (6)$$

By combining this with (5),

$$\int_S \tau \, dS + \int_{S_0} \rho_t w_t w_t \, dS_0 = g \int_V (\rho_e - \rho) \, dV \qquad (7)$$

Equation (7) may be rewritten as follows. Let us first divide it by V, thereby securing volume averages of the integrals. We have by simple geometry $S = 2\pi RH$ and $V = \pi R^2 H = S_0 H = \frac{1}{2} RS$ and can assume that ρ_t is approximately constant over S_0. We write

$$\frac{2}{R} \langle \tau \rangle^S + \frac{1}{H} \rho_t \langle w_t w_t \rangle^{S_0} = g \langle \rho_e - \rho \rangle^V \qquad (8)$$

where the angle brackets signify averages over the superscript quantities. Using primes to denote departures from S_0 averages and the Schwarz inequality, we can finally rearrange (8) to the form

$$(\langle w_t \rangle^{S_0})^2 = Hg \frac{\langle \rho_e - \rho \rangle^V}{\rho_t} - \frac{2H}{\rho_t R} \langle \tau \rangle^S - \langle (w_t')^2 \rangle^{S_0} \quad (9)$$

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