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CONTROLLED ATMOSPHERIC CONVECTION IN AN ENGINEERED STRUCTURE

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The momentum theorem of classical hydrodynamics is applied to a scheme for controlled atmospheric convention within a vertical tube of large height and diameter, open at both ends, for which the name *aerological accelerator* was previously suggested by the writers. The interior thermodynamic process is conceived as being moist adiabatic, although departures from this ideal case must be considered. The condensation and consequent latent heat release renders unnecessary any external drive, save for a proper supply of moist air. As discussed previously by the writers, the most important practical application of the device is the production of fresh water for ordinary uses from atmospheric water vapor. A year of daily soundings from the aerological station at Brownsville, Texas, is analyzed to examine the probable success of the procedure. The theoretical results are encouraging, but a host of questions and problems remain. Various of these are commented upon, and suggestions are made for further investigation of them.

A device of artificial construction within which the upward branch of an atmospheric convective system might be contained and controlled was described in two articles by Starr & Anati (1971 a, 1971 b), and also in a survey of humidity studies for the atmosphere by Peixoto (1971). The apparatus, designated by these authors as an *aerological accelerator,* consists mainly of a large tube extending vertically to a height above the condensation level of a surface air parcel, together with other accessories needed for satisfactory operation. A typical geometry was considered to be a circular cylinder with a radius of 50 meters and a height of 3 kilometers. The prime objective was to achieve a moist convective process within the tube, and an output of liquid water of considerable purity to satisfy various human needs. The great drawback to making an actual experimental installation is the engineering difficulty posed by the large size needed and the consequent high cost.

Although the production of fresh water was the purpose kept in view, other uses of the same type of device were mentioned in passing, as was also the possible arrangement of artificially conditioned intake air for testing purposes in a semi-full scale installation. As is illustrated below, artificial thermal forcing for experimental studies, if strong enough, could probably be done using a tube of much smaller height provided the intake air is nearly saturated. It appears that a sufficient source of heat for such a trial arrangement might be supplied by the surplus energy discarded by an electric power plant, especially a large modern atomic installation.

For the present application (fresh water production) we need much careful assessment, especially in view of the difficulty and expense of actual trial. To do this, it is necessary to have at least an approximate theory for the subject. In the subsequent sections we have therefore endeavored to do the following, (1) to formulate a closed system of simplified equations governing the action of the accelerator, assumed to be of the standard form mentioned, but of varying dimensions; (2) to apply the simple theory to obtain a statistical appraisal of the performance of the device under natural conditions at one possible geographical location; (3) to apply the simple theory to a unit for which conditions are the same as above, save that the intake air is moistened slightly by added evaporation; (4) to make general comments of a scientific and technological nature about the subject under consideration, especially in regard to the possible further course of its study.

CLOSED SYSTEM OF EQUATIONS

In the first place it should be pointed out that the set of equations given below relates to the mechanical aspects of the system alone. We assume that the mean densities inside and outside our tube are given by observation or otherwise known. The geometry of the accelerator is that given in Fig. 1. The symbols to be used are the following (with some variations):

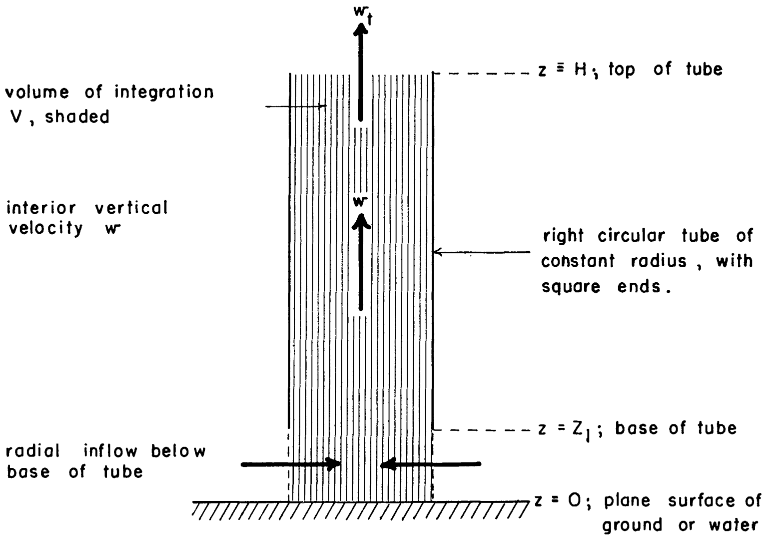

Fig. 1.
Schematic diagram of vertical cross-section through accelerator. See text and list of symbols there given.

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_o,	surface pressure
P_t,	pressure at top of tube
P_{xz}, P_{yz}, P_{zz},	vertical stress components across planes normal to x, y, z directions, respectively
R,	radius of tube
R_a,	gas constant for dry air
ϱ,	density in volume of integration
ϱ_e,	density of environment
ϱ_o,	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_o,	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, z directions, respectively
V,	volume of cylinder from $z \equiv 0$ to $z \equiv H$ (see Fig. 1)
v_R,	outward horizontal velocity normal to wall of volume of integration
w_R,	upward velocity parallel to wall of volume of integration
w_o,	vertical velocity at surface
w_t,	vertical velocity at top
x, y, z,	cartesian coordinates with z axis positive upward
Z_1,	height of base of tube

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

$$\varrho \frac{Dw}{Dt} = -\varrho \frac{\delta \Phi}{\delta z} + \frac{\delta Pxz}{\delta x} + \frac{\delta Pyz}{\delta y} + \frac{\delta Pzz}{\delta z} \tag{1}$$

$$\frac{\delta \varrho}{\delta t} + \frac{\delta \varrho u}{\delta x} + \frac{\delta \varrho v}{\delta y} + \frac{\delta \varrho w}{\delta z} \equiv 0 \tag{2}$$

It follows from Eq. (2) that we may write

$$\varrho \frac{D(\,)}{Dt} \equiv \frac{\delta \varrho (\,)}{\delta t} + \frac{\delta \varrho (\,) u}{\delta x} + \frac{\delta \varrho (\,) v}{\delta y} + \frac{\delta \varrho (\,) w}{\delta z} \tag{3}$$

so that Eq. (1) may be rewritten as

$$\frac{\delta \varrho w}{\delta t} = \frac{\delta}{\delta x}(P_{yz} - \varrho wv) + \frac{\delta}{\delta y}(P_{yz} - \varrho wv) + \frac{\delta}{\delta z}(P_{zz} - \varrho ww) - g\varrho \tag{4}$$

We now take a volume integral of Eq. (4) over V, making use of the divergence theorem. Thus we may write that

$$\frac{d}{dt}\int_V \varrho w dV \equiv -\int_S \tau dS - \int_S \varrho_R w_R v_R dS + \int_{S_o} (P_o - P_t)\, dS_o$$

$$+ \int_{S_o} \varrho_o w_o w_o dS_o - \int_{S_o} \varrho_t w_t w_t ds_o - g \int_V \varrho dV \tag{5}$$

It is now clear that the rate of accumulation of upward momentum in V is given, in the order of the integrals on the r. h. s. of Eq. (5), by (A) the frictional drain to S; (B) the advection of vertical momentum across S by v_R; (C) the net pressure force exerted in the vertical upon the fluid in V by the outside across the bottom and top; (D) the advection of vertical momentum across the bottom by virtue of w_o; (E) the advection of vertical momentum across the top by virtue of w_t; and (*F*) the gravity force acting on the fluid in V. We have assumed that $P_{zz} \equiv - P$, nearly enough, and that g is constant.

It is now necessary to introduce some assumptions peculiar to our particular problem. These are the following:

A. The conditions are steady with time for integrals in Eq. (5).
B. $w_o \equiv 0$ with sufficient accuracy.
C. $v_R = 0$ except below lower end of tube.
D. $w_R = 0$ nearly enough below lower end of tube, since the end is near the surface.
E. The environment is essentially at rest, and in hydrostatic equilibrium.
F. P_o and P_t are the same as in the adjacent environment at the same levels.

Applying these, we see that Eq. (5) reduces to

$$0 \equiv -\int_S \tau dS + \int_{S_o} (P_o - P_t)\, dS_o - \int_{S_o} \varrho_t w_t w_t dS_o - g \int_V \varrho dV \tag{6}$$

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 V in the undisturbed environment. We have, in view of our assumptions and using the subscript e to indicate environmental conditions,

$$0 = \int_{S_o} (P_o - P_t)_e\, dS_o - g \int_V \varrho_e\, dV \tag{7}$$

combining this with Eq. (6)

$$\int_S \tau\, \mathrm{dS} + \int_{S_o} \varrho_t w_t w_t dS_o \equiv g \int_V (\varrho_e - \varrho)\, dV \tag{8}$$

We thus regain the contention made at the end of the previous paragraph (compare Starr & Anati 1971 b). Eq. (8) may be rewritten in many ways. Let us first divide it by V, thus securing volume averages of the integrals. We have by simple geometry $S \equiv 2\pi RH;\ V = \pi R^2 H \equiv S_o H \equiv {}^1/_2\, RS,$ therefore

$$\frac{2}{R}\overline{\tau}^{\,S} + \frac{1}{\mathrm{H}}\overline{\varrho_t w_t w_t}^{\,S_o} \equiv g\, \overline{\varrho_e - \varrho}^{\,V} \tag{8 a}$$

where the bars signify averages over the superscript quantities, although each term as a whole is a volume average. It is admissible, under conditions of interest to us, to take ϱ_t to be constant over S_o. Accordingly, we may now write

$$\overline{w_t w_t}^{S_o} \equiv H g \overline{\frac{\varrho_e - \varrho}{\varrho_t}}^{V} - \frac{2H}{R\varrho_t}\overline{\tau}^{S} \tag{9}$$

where the gravity term on the right now contains the buoyancy force per unit mass as a coefficient of H.

Using primes to denote departures from S_o averages, we next write, in agreement with the inequality of Schwarz, that

$$\overline{w_t w_t}^{S_o} \equiv \left(\overline{w_t}^{S_o}\right)^2 + \overline{(w_t')^2}^{S_o} \tag{10}$$

the last term being the vertical eddy transport of vertical momentum across the top. We now have that

$$\left(\overline{w_t}^{S_o}\right)^2 = \mathrm{Hg}\overline{\frac{\varrho_e - \varrho}{\varrho_t}}^{V} - \frac{2H}{\varrho_t R}\overline{\tau}^{S} - \overline{(w_t')^2}^{S_o} \tag{11}$$

which enables us to calculate an upper bound for $\overline{w_t}^{S_o}$, if data are furnished for the first two terms on the right of Eq. (11). In a realistic case it is not likely that the last, or variance, term would be too important, although the interior motions within the tube would be expected to be turbulent. Probably an error of not more than a few per cent is made by neglecting it in our case. The middle term on the right contains $\overline{\tau}^{S}$ multiplied by the aspect ratio H/R. The variations of ϱ_t for currently feasible heights H of the tube are not large. For a given value of the stress, the importance of the wall friction increases linearly with H and decreases inversely with increasing tube radius. On the other hand, for a given percental density difference between the exterior and interior, the effect of the buoyancy contribution is independent of R and increases linearly with H. Therefore, if it is desired to decrease the necessary minimum height as much as possible to reduce construction costs, and still achieve a given vertical velocity $\overline{w_t}^{S}$ (neglecting the vertical eddy transport of vertical momentum), it is advantageous to increase the density difference and to increase R.

What we have assumed leads to the result that for a density difference of 1 per cent, a height of 3 km, a stress of 2 dyne cm-2, and a radius of 50 m, the first term predominates over the second by one order of magnitude and leads to a vertical efflux velocity of about 17 m sec-1. About the same result follows if H is reduced to 300 m and the density difference is increased to 10 per cent - - a possible situation in the case of experimental thermal forcing.

Thus far in the development no use has been made of an equation of state, so that the results follow even though the medium is partly liquid and partly gaseous (or even though it may contain suspended solids), so long as the averages are accurately defined. However, in order to explore further the properties of our system conveniently, it is desirable to make some assumptions in this direction, and also to relate the stress in an approximate fashion to the mean vertical velocity. For the time being we assume in essence that the buoyancy effect is specified by data and not generated by the interior motions themselves. In other words, except for writing an approximate equation of state, we leave the thermodynamic part of the theory for consideration later.

Under conditions of pressure and temperature that concern us, air with no water substance in any of its phases is subject to the ideal equation of state within close limits. Since water molecules in water vapor are lighter than the average air molecules, the effect of an admixture of the former into the latter decreases the density, other things being the same. This effect may be translated into a fictitiously elevated temperature, the virtual temperature T^*, so that the ideal equation may still be used with the gas constant for air free of all water substance (see Brunt 1942, Starr & Anati 1971 b), namely

$$P = R_a \varrho T^* \tag{12}$$

The use of T^* does not, however, help us to provide for the effect on the mean density of the presence of liquid cloud and rain drops. This cannot be done in a simple way, and we shall neglect it, although the possible influence of this omission should be kept in mind. We readily see that the use of Eq. (12) leads us to the relation

$$\frac{\overline{\varrho_e - \varrho}^V}{\varrho_t} = \frac{\overline{T^* - T_e^*}^V}{T_t^*} \tag{13}$$

in our notation.

The stress occurring in Eq. (11) is not ordinarily measured with ease. For this and other reasons, it is desirable to relate it approximately to $\overline{w_t}^{S_o}$. Since this mean velocity is more or less representative of conditions at interior levels within a tube of moderate height (as is also $\overline{\varrho_t}^{S_o}$), we shall simply apply the formula from friction layer theory and write (see Schlichting 1968)

$$\overline{\tau}^S = \overline{\varrho_t}^{S_o} C_D \left(\overline{w_t}^{S_o 2}\right) \tag{14}$$

We see that with the acceptance of the validity of the assumptions underlying Eq. (13) and (14), Eq. (11) now may be approximated as

$$\left(1 + 2C_D \frac{H}{R}\right)\left(\overline{w_t}S_o\right)^2 \equiv Hg \overline{\frac{T^* - T_e^*}{T_t^*}}^V - \overline{(w_t')^2}S_o \tag{15}$$

For low aspect ratio (i. e., squat) tubes, which might perhaps be more likely choices for some applications, for which $2C_D H/R \ll 1$, we have

$$\left(\overline{w_t}S_o\right)^2 \equiv Hg \overline{\frac{T^* - T_e^*}{T_t^*}}^V (1 - \varepsilon) \tag{16}$$

to the first order of small quantities, ε being given by the inequality and the eddy term being omitted. For the value of the drag coefficient C_D we shall use 1.3×10^{-3}.

We now see that we have in Eqs. (15) and (16) an approximate solution to the mechanical problem posed by our convective system, in the sense that if we are given the thermodynamic forcing as represented by the virtual temperatures in the buoyancy term, we can calculate the gross mechanical properties like average velocities, mass transports, and other integral effects with adequate accuracy in most cases. Under certain circumstances, involving further assumptions, the buoyancy term itself becomes partially determined by the motions and partially by the properties of the environment, as already touched upon. In such cases (adiabatic motions whether moist or dry) eventually the total behavior, assumed steady, is fixed by the environment, since the buoyancy in turn fixes the motions. However, if artificial or other heating of the intake air takes place, or the adiabatic conditions are interfered with in some way, then the system becomes much more complex.

The well-known researches of Von Bezold, Hertz, Neuhoff, and others around the turn of the century (see, e. g., Brunt 1942) into the thermodynamic processes of dry and moist air resulted in much new insight into atmospheric problems. One result was the designing of a variety of thermodynamic charts which are so convenient for various operations in meteorological work concerned with cloud formation and development of precipitation. However, it soon became evident that these considerations could not alone explain various features of entire convective systems like thunderstorms. One reason for this situation is that these units are not, in a manner of speaking, one dimensional. In an actual updraft the entering air need not simply come from the bottom, but rather it may also originate mostly at some intermediate level. Moreover, the rising column may receive increments from parcels entrained from the environment, on its entire way. These parcels may be drier and have a lower temperature, thus hindering the convection.

In contrast, convective updrafts in our apparatus have a pinpointed source in the lowest, normally most moist layers of the atmosphere. Likewise the presence of the tube precludes the entrainment of air having other properties. In special arrangements, particularly in research versions of the device, the intake air may be even further heated and moistened to enhance the convection. Whatever this controlled conditioning may be, in any case the updraft is fed by an air supply of homogeneous properties. It thus appears that the ideal of a uniform one-dimensional process can be achieved rather closely, with the consequence that the thermodynamic actions can be portrayed rather successfully using one or another of the standard forms of the thermodynamic diagrams.

Having made the remarks above, we shall not recapitulate the steps through which the buoyancy term might be estimated from meteorological soundings, (*A*) because they are well known by meteorologists and are discussed in standard textbooks, and (B) because some discussion of the details has been given by Starr & Anati (1971 b). The use of the procedure in the following section will also illustrate its application under the simple assumption of adiabatic motion in both the dry and moist stages.

What we have done in the development given above is to apply the momentum theorem of classic hydrodynamics to our system. Much of the technique used was borrowed from the studies of the first author on momentum and energy integrals for the ideal case of surface waves in water. In the present paper an analysis in terms of energy integrals has not been entered upon, although this presumably might be done.

A CLIMATOLOGICAL STUDY

In examining the actual conditions for the successful operation of an aerological accelerator at any particular station, we soon discover that the day-to-day variation in certain parameters, notably the ground-level mixing ratio, is large enough to render any statistical conclusion rather meaningless, unless based on a relatively large number of samples. For this reason, and also for the purpose of looking into the diurnal and seasonal variations, it was decided to examine a whole year of data, taken twice daily, at a suitable location.

Our computational model is based on the above set of equations, and simulates an aerological accelerator located at Brownsville, Texas. The radius of the accelerator tube was taken to be 50 meters, and its top was assumed to reach the 700 mb level (roughly 3 km in height). The data year chosen was 1958 (the first calendar year after the beginning of the IGY program, and also the subject of many other studies).

In choosing Brownsville, we were partly motivated by some encouraging preliminary results and partly by the need for water in this general area. Our source of surface and upper-air temperature and relative humidity data was the "Daily Bulletin of the U.S. Weather Bureau, Part II." The soundings examined were taken at 00.00 and 12.00 hours G.M.T., or 18.00 and 06.00 hours local time, respectively. The results for the two synoptic times were computed separately for comparison.

Our numerical model was designed to compute various quantities for each sounding separately, i. e., at half-day intervals. From these quantities means were derived for each month. The results are summarized in Table 1. The operating time denotes the percentage of days during which the device was active, the buoyancy of the air column within the tube being positive in these cases. The vertical velocity, water production rate, and rate of air ejection given in Table 1 are the averages of these quantities for the *operating* days of the month and may be called *typical values,* not to be confused with monthly means. The water production rate refers to the *maximum* amount releasable from a ground-level parcel of air rising through the tube. Probably a considerable fraction of this amount will be ejected through the top of the apparatus in small droplets. We neglect for the moment other beneficial aspects such as additional local rain induced by the process, since it is clear this portion will not be available for immediate and direct use or storage. At the present state of knowledge, it is difficult to estimate accurately this loss factor; but as suggested in a previous article (Starr & Anati 1971 b), roughly half of the amount indicated in Table 1 would probably be a fairly realistic expectation. It must be stressed, however, that this uncertainty does not apply to the rate of air ejection through the top, with its consequences on any possible application of the aerological accelerator for pollution control.

The total amounts of water produced and air removed during the various months are given in Table 2. We can see that the most active period is in the summer months. Actually, 85 per cent of the water production and 86 per cent of the air removal occur in the relatively short period between 15 May and 28 October. It is interesting to note though that the most favorable days are not necessarily found during this period. The three most productive days are shown in Table 3, with only one of them, 15 October at 00.00 G.M.T., occurring in the active period mentioned above.

Another interesting point worthy of attention is the dependence of the

Table 1.

Summary of output by months for two synoptic hours, of an accelerator located at Brownsville, Texas, during the calendar year 1958. Values are theoretical, computed from formulae given in text. All units metric.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Synoptic hour	12.00 G.M.T. or 06.00 L.S.T.											
Operating time (%)	10	11	00	03	13	57	61	39	43	14	06	00
Vertical velocity (m/sec)	8.4	8.8	—	1.3	8.0	7.9	7.4	6.7	6.4	11.0	1.7	—
Water production (10^2 tons/hour)	15	16	—	03	16	16	15	14	13	23	03	—
Rate of air ejection (tons/sec)	68	71	—	11	64	62	59	53	51	88	14	—
Synoptic hour	00.00 G.M.T. or 18.00 L.S.T.											
Operating time (%)	16	21	16	00	74	90	94	71	93	71	40	10
Vertical velocity (m/sec)	7.9	8.0	7.8	—	9.6	8.4	9.7	8.8	8.5	8.9	6.5	9.8
Water production (10^2 tons/hour)	12	13	13	—	15	14	16	14	15	16	11	17
Rate of air ejection (tons/sec)	64	65	63	—	77	66	76	70	67	71	53	80

Table 2.

Total amount of water produced and total amount of air ejected, by months. Values estimated for all operative days from 00.00 and 12.00 G.M.T. soundings. All units metric.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Monthly amount of water produced (10^4 tons)	13	15	07	03	50	78	90	56	72	55	17	06
Monthly amount of air ejected (10^6 tons)	23	26	13	05	89	124	144	93	110	83	28	10

various pieces of output on the radius of the tube. Having a larger radius would affect the process not only directly, through the increased cross-sectional area, but also by reducing the relative effect of friction at the walls. For example, if we take in our model a radius twice as large (100 meters instead of 50), we can expect the average upward flux of air, and consequent water production rate, to increase by slightly more than a factor of 4. The climatological percentage of operating time would, however, not be altered by this change, and the vertical velocity would be expected to increase only slightly, as is seen from Eq. (11). Indeed, checking a number of days chosen at random from among the operative days, it was found that for a 100-meter radius the vertical velocity increased by a factor of 1.03 and the water production rate by a factor of 4.13 compared to the 50-meter radius case.

EFFECTS OF ARTIFICIALLY AUGMENTED HUMIDTY INPUT

We have suggested in one of our previous articles (Starr & Anati 1971 b) that a relatively small increase in the mixing ratio of the ground-level air would have a marked effect on the performance of the proposed device. In order to secure a quantitative estimate in this regard, we may now check, for example, to what extent the results presented so far would be altered by an increase of one gram of vapor per kilogram of air in the mixing ratio at the intake. This was done keeping the same pressure and temperature as observed for the actual

Table 3.

Velocity, water production, and air ejection for the three most active sounding conditions during the year. All units metric.

Date	28 Jan. 12.00 G.M.T.	4 May 00.00 G.M.T.	15 Oct. 00.00 G.M.T.
Vertical velocity (m/sec)	17.6	21.6	14.8
Rate of water production (10^2 tons/hour)	32	35	32
Rate of air ejection (tons/sec)	183	218	150

ground-level air parcels, and subject to the condition that the resulting moisture value be no greater than the saturation mixing ratio for the same pressure and temperature. In these rather rare cases saturation was assumed. We may note that the actual observed mixing ratio of the ground level air lies between the extremes of 4 and 23 grams per kilogram, with an average around 18. The increase used therefore constitutes about a 5 per cent change in the water content of the air to be lifted through the tube.

The results are shown in Tables 4 and 5, which are comparable to Tables 1 and 2. The characteristic values of the vertical velocity, the water production rate, and the rate of air ejection are not much changed. In many cases they increase to some extent, while in some others they decrease as a consequence of the fact that on certain days during which the device was inoperative under the original conditions, it now became weakly operative due to the change. Such days were included in the new averages. The major effect is seen in the total amount of water produced. A yearly total of about 8 million tons was obtained compared to about 4 million tons for the original case.

The significant point to be made here is that, according to the calculations, a large increase of the water produced is gotten from what might appear as only a slight preconditioning of the intake air. We therefore suggest that further scientific, and, later, engineering studies are in order to investigate in some detail possible methods for accomplishing this desired result as efficiently as can be done.

DISCUSSION

If the apparatus now under discussion is to be considered purely from the basis of commercial fresh water production, the price of the fresh water so obtained is high, although just how high it might be depends upon the location where its cost is to be compared with the cost of other possible sources of supply and various other factors. For one thing, as time goes on, more efficient design features may be conceived, and inexorably more demand for water will arise for domestic and industrial uses from one generation to the next. An anticipated rather high purity of the water may also be important for special uses. On the other hand, a device of the kind visualized could have other useful functions, so that a combination of benefits could lessen the economic strictures. In the end it can no doubt be said that the first instances of actual construction will have to be justified to a large extent as scientific research endeavors. Thus, since our subject is just at the beginning of the "talking

Table 4.

Summary of output exactly similar to that given in Table 1, save that the mixing ratio of intake air is taken to be artificially increased by one gram per kilogram through evaporation by proper arrangements. All units metric.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Synoptic hour	12.00 G.M.T. or 06.00 L.S.T.											
Operating time (%)	19	14	00	10	23	60	71	55	63	24	10	00
Vertical velocity (m/sec)	6.9	8.9	—	5.0	7.5	9.9	8.8	8.0	6.5	8.3	3.1	—
Water production (10^2 tons/hour)	12	16	—	10	16	21	19	17	14	17	06	—
Rate of air ejection (tons/sec)	57	72	—	40	60	78	70	64	52	66	25	—
Synoptic hour	00.00 G.M.T. or 18.00 L.S.T.											
Operating time (%)	32	36	32	13	81	93	100	90	100	77	53	10
Vertical velocity (m/sec)	8.7	8.0	8.0	4.9	11.6	10.8	11.4	10.0	10.9	10.7	9.0	13.0
Water production (10^2 tons/hour)	15	14	14	08	19	19	19	16	20	21	17	24
Rate of air ejection (tons/sec)	71	65	65	40	92	85	89	78	85	85	72	106

Table 5.

Total amount of water produced and total amount of air ejected, by months, for conditions at Brownsville, but with humidities augmented by one gram per kilogram. Values estimated for all operative days from 00.00 and 12.00 G.M.T. soundings. All units metric.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Monthly amount of water produced (10^4 tons)	26	24	16	75	72	108	122	90	105	74	34	86
Monthly amount of air ejected (10^6 tons)	46	41	28	12	118	164	186	142	153	109	53	14

stage", the above items together with many others are in need of much discussion. Some of these more detailed considerations are the following.

1. We have retained, as a point of departure, the assumption that the process within our tube is pseudoadiabatic – a point concerning which much more study is needed, as was stressed in our previous papers. Nevertheless it is interesting to note that on this basis the experimental addition of one gram of water per kilogram to the intake results in a condensing out of less than an additional one gram per kilogram. This can easily be seen from the shape of the lines on a tephigram. It follows therefore that the larger monthly total amounts of water produced shown in Table 5 for the augmented input are due mainly to the increased number of operative days and to the higher vertical velocities attained. The simple addition of still larger amounts of water vapor to the intake should be accompanied by still larger effects, as far as these calculations go. One must, however, remind oneself that the higher vertical velocities then obtained would no doubt expel a higher percentage of the condensate from the top of the tube in a typical case.

Were we to start with intake air of rather small natural humidity, into which considerable amounts of water were evaporated from sea water at the intake, the action would then partake something of the nature of a desalinization process. From the above discussion it follows that only a fraction of the added water vapor could be condensed into liquid — unless the tube were exceedingly tall.

2. It is instructive to note that, according to Table 5, about 10^9 tons of air were passed into the intake during the year. Supposedly one gram of water was added to each kilogram, so that the total evaporated water was 10^6 tons. To visualize this amount we might think of it as a loss by artifically induced evaporation of one meter per year from an area of one square kilometer. If this evaporation were actually achieved by some proper method, as we have suggested in the previous article in this journal, from sea water in an almost closed lagoon so that communication with the open sea can be controlled, in principle the device would separate out about 3×10^4 tons of minerals per year. This is, of course, an ideal figure, but would nevertheless represent a by-product to the 8×10^6 tons of fresh water produced, as indicated by Table 5, likewise on an ideal basis. If water of higher mineral concentration were to be utilized, the outcome would, of course, be higher. Thus, water from the Dead Sea might yield something like 2×10^5 tons of residue per year were we to assume that other processes would be comparable to those at Brownsville. See item 5 below on the use of a shorter tube.

3. Since all the tables given include 18 L.S.T. soundings, it is quite probable that the diurnal maximum of activity is missed because it is present earlier in

the afternoon. On the other hand, the corresponding minimum of activity is perhaps well represented by the 06.00 L.S.T. soundings. On this basis it is quite possible that all the averages given are rather conservative estimates.

4. In the present paper we have limited ourselves to some of the more scientific aspects of confined convection, although certain engineering topics such as the size and purpose of the device must necessarily be given consideration. Thus we have avoided the more strictly technical questions such as the need for controlling and monitoring mechanisms, the strength of materials to be used in construction, the means of support of a large tube, whether it be built on a steep orographic escarpment or be of the balloon type (a double walled tube could itself be made lighter than air), etc. All these are, of course, important problems, but in reality are too extensive to be treated here and are therefore relegated to possible future discussions. Generally speaking they will require much mutual give and take between engineers and scientists. Some topics of this kind were touched upon in our previous papers.

5. In one of our previous papers we mentioned the possibility of constructing a purely experimental unit, smaller in diameter than a full-scale model, in which the updraft would be forced mechanically by fans, let us say. It is also possible (with different results, of course) to consider thermal forcing, through the use of a highly heated input that could also be saturated, in a full-diameter, but shorter tube — again for experimental objectives. If use is made of the numerical scheme already tested above, the behavior of such models is easily determined. Doubtless the results give the general properties of an actual device.

In order to investigate possibilities, the model used above was applied to a tube extending vertically only 50 mb or roughly 440 meters. The radius was again taken to be 50 meters. However, the intake air was assumed to be saturated at a temperature of 30°C. For purposes of comparison with our previous results, the environment was assumed to be given by the twice daily soundings at Brownsville for 1958 used before. The calculations showed practically no seasonal change, which is not unexpected. The vertical velocity was about the same as in the previous cases, namely averaging 8.3 m sec–1. The water production rate was smaller, 320 tons per hour on the average, when computed as previously. The total water production per year was not much less than in the case of natural intake air and tall tube, namely 2.8 million tons. This is because the apparatus was considered to be working continuously for the whole year, compared to 39 per cent of the time with the natural input (21 per cent in the morning and 57 per cent in the evening).

How much energy in the form of heat added would be required to condition the natural intake air to saturate it at 30°C? Again there is little variation with season. The average value turns out to be about 1700 megawatts. This rate is about the size of waste heat rejection of a large atomic power plant, say of 800 megawatt capacity, which could therefore be utilized in such experimentation as is now being considered. Since the waste heat must in any case be removed, this may constitute an added benefit of our device, but the subject becomes greatly complicated by formidable technical, environmental, and therefore also ecological problems. Except in the case of oceanic locations, the supply of water becomes a problem, for example. Nevertheless the order of magnitudes is correct for scientific trial purposes. Actually by raising the temperature of the saturated intake beyond 30°C, very intense action could be secured with the short tube now being considered.

6. Technological developments of any magnitude, if they involve a new application of scientific principles, often require much thought and perfecting before fair amounts of success are attained from a practical viewpoint, especially when economic factors are a limitation as is currently the case. At the beginning, although the proposition may be logically plausible, many drawbacks exist, not the least of which is a simple unfamiliarity with the subject. The latter appears as being artificially generated (as it indeed must be) and hence not be taken seriously. Such psychological strangeness only gradually wears off as discussion takes place and new additional ideas are introduced to increase the efficiency of the projected construction or enterprise, which thus counteract some of the intuitive objections that might be present. Finally a moment is reached when the general idea is accepted as a matter of course, and it is the technical details which are then confronted, perhaps successfully. The reader can no doubt himself supply various examples of such a chain of events attending the final success of many a technological breakthrough in the past.

7. The analytical approach outlined in the first part of this paper may be viewed as a rudimentary theory for the simplest kind of smokestack or chimney (see Starr & Anati 1970 a). The difference in our case is the mode in which the density difference betwen the inside and outside is created and maintained. As is usual for a theory concerning a subject such as ours, it enables us to make certain predictions on the basis of data, as we could do for the conditions at Brownsville. Many more locations should be thus examined, because it is often impossible to evalute conditions accurately enough from the general appearance of the soundings.

To pursue the matter further, a more detailed theory is needed for these and other purposes. It could be in the form of a numerical solution, say for an initial value problem giving the transient response to a given forcing. It would then be seen whether and when a steady mean flow develops, and whether spatially and/or temporally periodic solutions might be present. The relative importance of wall friction no doubt has much to do with these questions.

8. As we have previously stated elsewhere, it should perhaps be again pointed out that the effluent from the top of the accelerator could possibly introduce certain changes in the local meteorology. By exhausting large quantities of saturated air above the lifting condensation level, it is quite possible, under a variety of normally occurring conditions, for cumulus activity to develop above the tube. During moist summer conditions in many parts of the world, towering cumulus and even thunderstorm activity might be triggered by the accelerator exhaust. Local increases in precipitation might occur from the shower activity originating from these induced cumulus clouds. It is less likely, but still conceivable, that increased cirrus coverage might also result from the cumulus activity in the prevailing downwind direction from the tube.

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