Convective Mixing of Water with Brine Around the Periphery of a Vertical Tube

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ABSTRACT

Laboratory experiments were conducted in a closed system to study mixing attained by injection of water into brine through a vertical tube. The influx of brine of uniform concentration into rising fresh water was measured. Mixing was also studied for stably stratified brine and the changes in brine concentration due to water circulation were recorded. Several experiments were performed in stratified brine and later the convective mixing of water with brine in the presence of a dissolving boundary was studied.

The experimental results indicated that the extent of mixing is mainly dependent on the ambient brine concentration, rate of water injection and the vertical distance that the buoyant fluid is allowed to rise freely.

INTRODUCTION

In the practice of washing cavities in massive salt formation it is general knowledge that the method of reverse circulation, intermediate injection and bottom production produces greater cavity radii above the injection level than below it. However, the knowledge of the mechanics of convective mixing of the injected water with brine in the cavity and its subsequent role in total salt dissolution is rather limited.

In the past two decades a great number of theoretical and experimental studies have provided a considerable amount of information on the mechanics of the process of fluid rising in an extensive medium. The majority of these studies have been made in the field of heat transfer. The analogous mass transfer phenomena have received a great deal of attention in the areas of meteorology, air pollution control and oceanography.

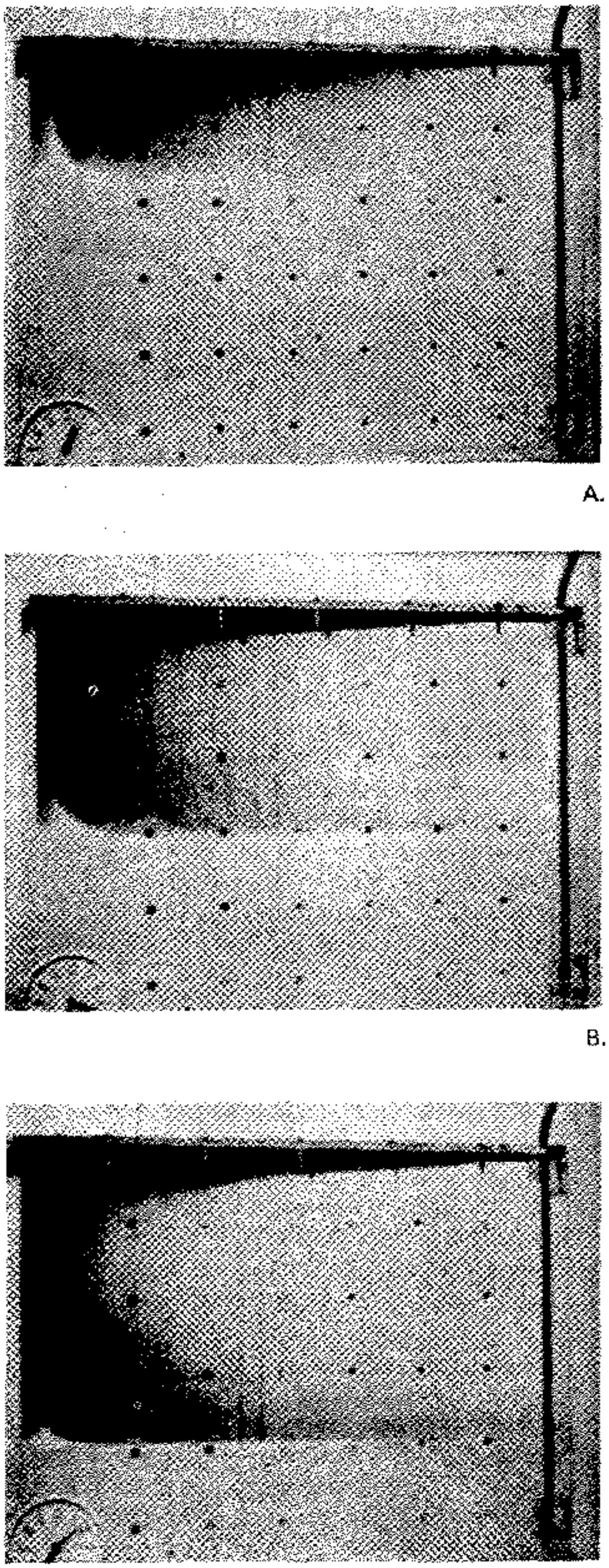
Yih (1951) studied the transition from laminar to turbulent flow in a heated plume. Rose et al. (1952) carried out experiments with a gas flame on the floor of an airtight room and studied the vertical velocity and temperature distribution of plumes. Morton et al. (1955) developed theories of convection from maintained and instantaneous sources of buoyancy, applicable to stratified fluids. Fujii (1962) analyzed mathematically the natural convection above a horizontal line heat source and a point source. Briggs (1969) summarized a total of 150 previous investigations on plume rise. Hewett et al. (1970) studied simulated smokestack plumes in laboratory and measured temperatures in horizontal plume cross sections. Chen et al. (1971) studied the flow field induced by lateral heating in a stably stratified brine of constant gradient.

The purpose of this study was 1) to investigate the convective mixing of water and brine due to injection of water into brine through a vertical pipe; 2) to study the effect of the water-brine mixing on salt dissolution in the process of solution mining of salt.

APPARATUS AND PROCEDURE

For water-brine mixing studies a wedge-shaped container, made of one-half inch thick clear Lucite plate was utilized. The model simulated a 30 degree segment of a cylinder with 23" radius and 17 5/8" height. There were thirty resealable sampling holes on one side of the model arranged in an array of five rows and six columns with adjacent holes 3" apart. Nine more sampling holes were located in a radial arrangement on the lid of the model. A hole with .434 inch diameter had been drilled at the axis of the model. A Tygon tube with 7/16" (.437) O.D. and 5/16" I.D. was tightly fitted into the hole and used as an injection tube. The inlet was positioned 1" from the bottom of the model. A glass tube with 7/32" O.D. and 1/8" I.D. was used as the tail pipe. The production level was 1/4" from the bottom.

A simple technique was devised to measure the brine entrainment. A small amount of dye was introduced to the injected water. The average dye concentration in water was about 200 ppm which did not change the water den-



A.

B.

C.

Figure 1. Mixing of dyed water and brine over 7 hour period. (a) mixing after 1 hr. 2 min.; (b) mixing after 3 hrs. 36 min.; and (c) after 7 hrs. 8 min.

sity significantly. Upon mixing, the entrained brine assumed the dye coloration and could be measured. In experiments conducted for brine of uniform concentration the mixed fluid rose to the top of the model and upon deflection from the model lid moved horizontally away from the well axis. The continuation of this process created a zone of mixed (colored) fluid with a horizontal front moving down the original brine in a piston-like manner (Fig. 1 a–c).

The changes in brine concentration in the model were determined by means of brine samples taken through the sampling holes. Hypodermic syringes were used for sampling and the concentrations were determined with the help of a refractometer.

BRINE OF UNIFORM CONCENTRATION

The first set of experiments conducted were aimed at studying the brine entrainment into the rising injection water.

Experiment No. 1

The Model was filled with saturated brine (ρ = 1.2019 at 24°C). The rate of injection of fresh water was 1 cc/min. The temperature of the water was kept constant using a temperature bath. In Figure 2 the cumulative volume of

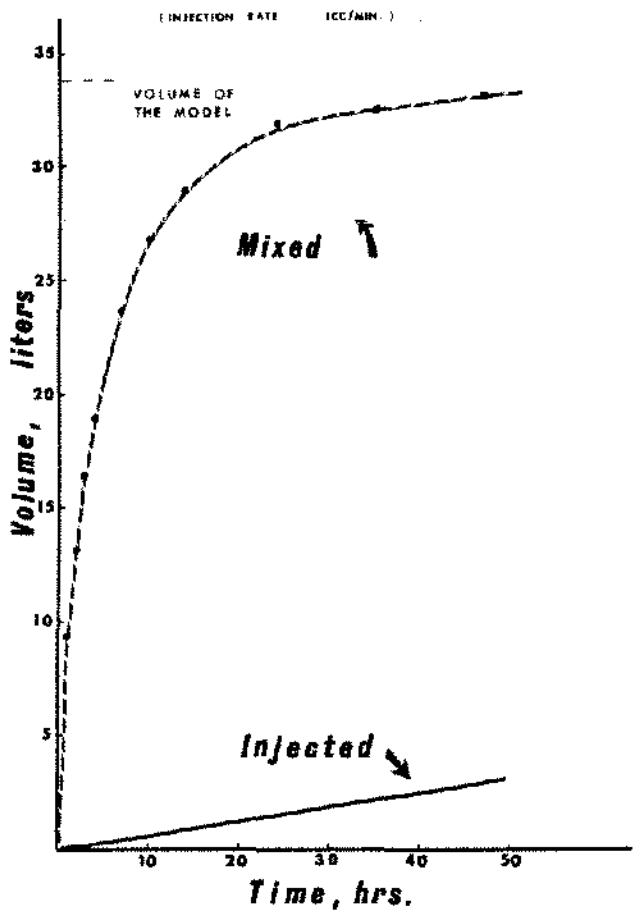


Figure 2. Volume of mixed fluid versus time.

the mixed fluid is plotted as a function of time. At the time when the slope of this curve becomes equal to the constant rate of injection the mixed fluid front has passed the inlet level. The indication is that for the very low rates of injection there is no mixing below the inlet. Figure 3 shows the change in vertical concentration and the development of salinity gradient.

Experiment No. 2

The brine concentration was 18.3% by wt. (ρ = 1.1413). The rate of water injection was the same as in experiment 1 (1 cc/min.). In order to provide a qualitative comparison between the two experiments the quantity mixing ratio was defined which could be interpreted as

$(q_z - q_o) / q_o$

where

q_z = the flow rate of rising fluid at distance z from inlet

q_o = Rate of water injection

Figure 4 shows the mixing ratio as a function of model height. The dashed curve refers to experiment No. 1. A comparison of the two curves shows that the mixing ratio decreases as the density of the bulk decreases.

Experiment No. 3

The brine in the model was saturated and the rate of injection was 9 cc/min. Figure 5 shows lower mixing ratios for this run compared to experiment No. 1 with q = 1 cc/min. The indication is that the rate of growth in the volumetric flow rate of the rising fluid decreases as the rate of water injection increases.

BRINE OF NON-UNIFORM CONCENTRATION

In the previous experiments it was shown that the fresh water injection into brine of uniform concentration will create a vertical salinity gradient in the brine. This technique was used to initiate a gradient in brine concentration for the following experiments.

Experiment No. 4

The run was started by introducing dye to the fresh water which was being injected at the rate of 1 cc/min. The ascending fluid behaved somewhat differently to the rise in uniform concentration brine. Portions of ascending fluid, during the course of rise, upon reaching the levels of equal densities came to rest. The continuation of this process developed the type of envelope shown in Figure 6.

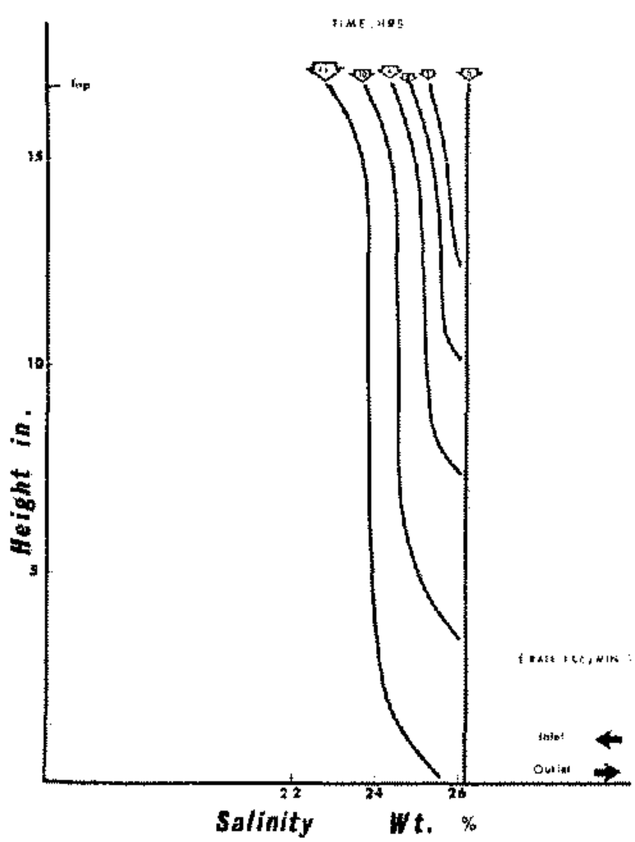


Figure 3. Changes in profile with time.

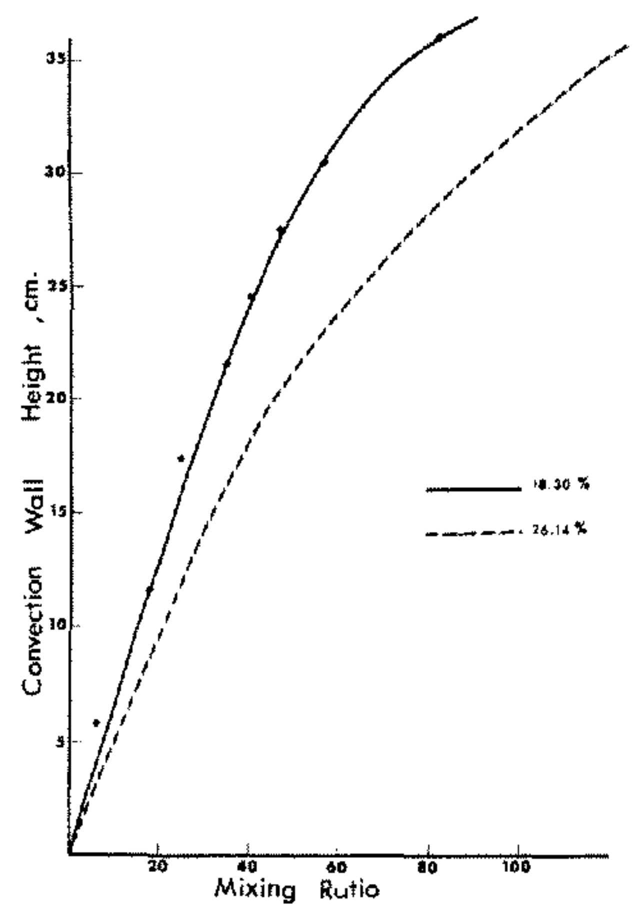


Figure 4. Effect of concentration on mixing ratio.

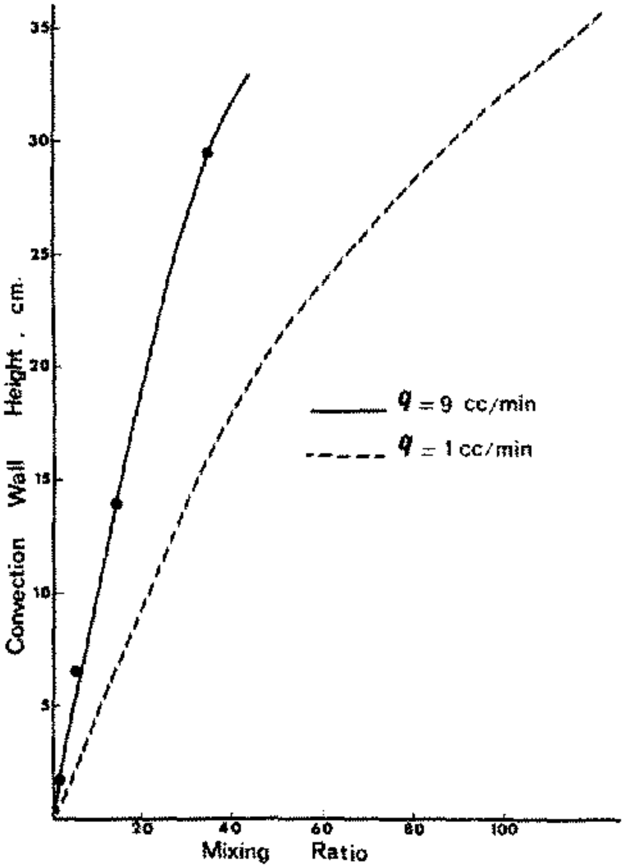


Figure 5. Effect of rate of injection on mixing ratio.

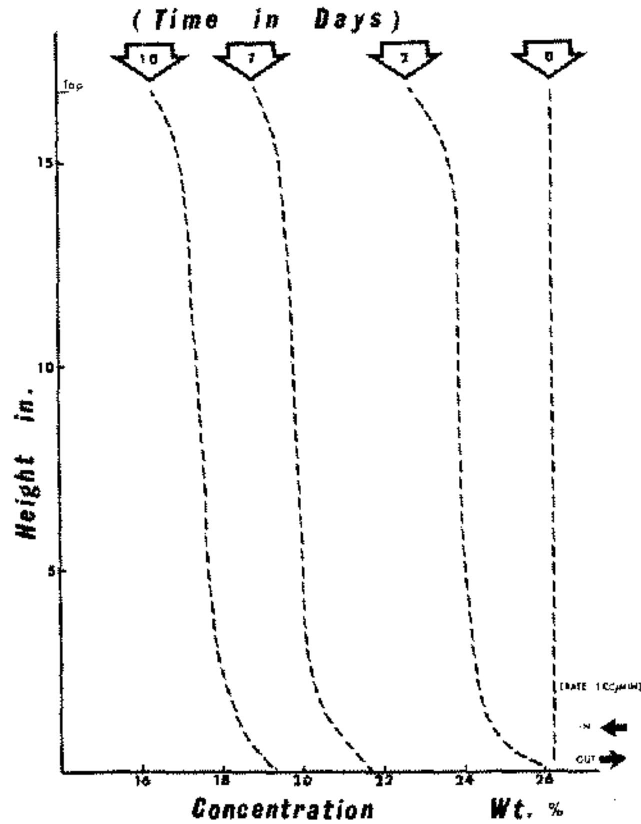


Figure 7. Lateral shift in profile.

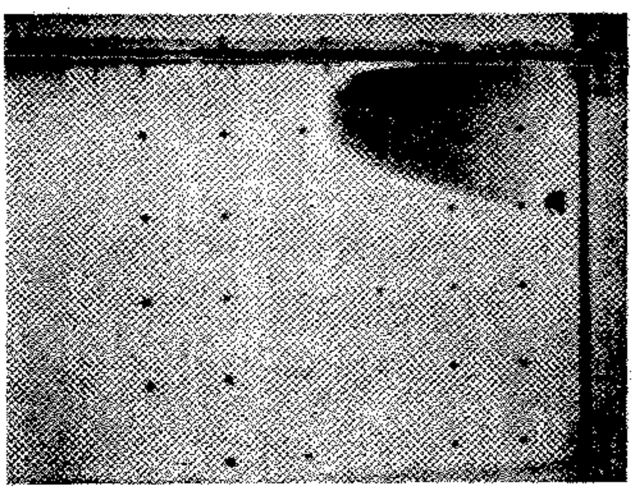


Figure 6. The color fluid envelope.

The parabolic shape of the mixed fluid front suggest that the gradual decrease in volumetric flow of ascending fluid which begins at some level during the rise is non-linear. Figure 7 shows the regression of the brine salinity profile for the entire length of the run (10 days). This figure indicates that for a given injection rate the change in the profile occurs in lateral shifts to lower concentrations without change in shape once a certain equilibrium shape is reached.

Experiment No. 5

Since the upward motion of the ascending fluid creates movements within the bulk fluid, an experiment was run to study the induced motion in the bulk fluid. To that end a column of dyed fluid was established in the nonuniform ambient brine (Fig. 8a). The deformation of this column due to induced motion in the bulk fluid is shown (Fig. 8 b–c). As Figure 8b indicates in the lower part where the entrainment occurs the motion is toward the axis. In the upper part, where the mixed fluid comes to rest incrementally the bulk fluid flow is away from the axis of the model. There are two peaks in the lower deformed dye column (Fig. 8c). The lower peak is located at the inlet level. The second peak is located about one inch above the first one. The absence of movement in bulk fluid between the two peaks suggests laminar flow of the ascending fluid in that zone.

STRATIFIED BRINE

The results of previous experiments verified the existence of a salinity gradient within the rising fluid. Due to the following limitation the determination of the salinity

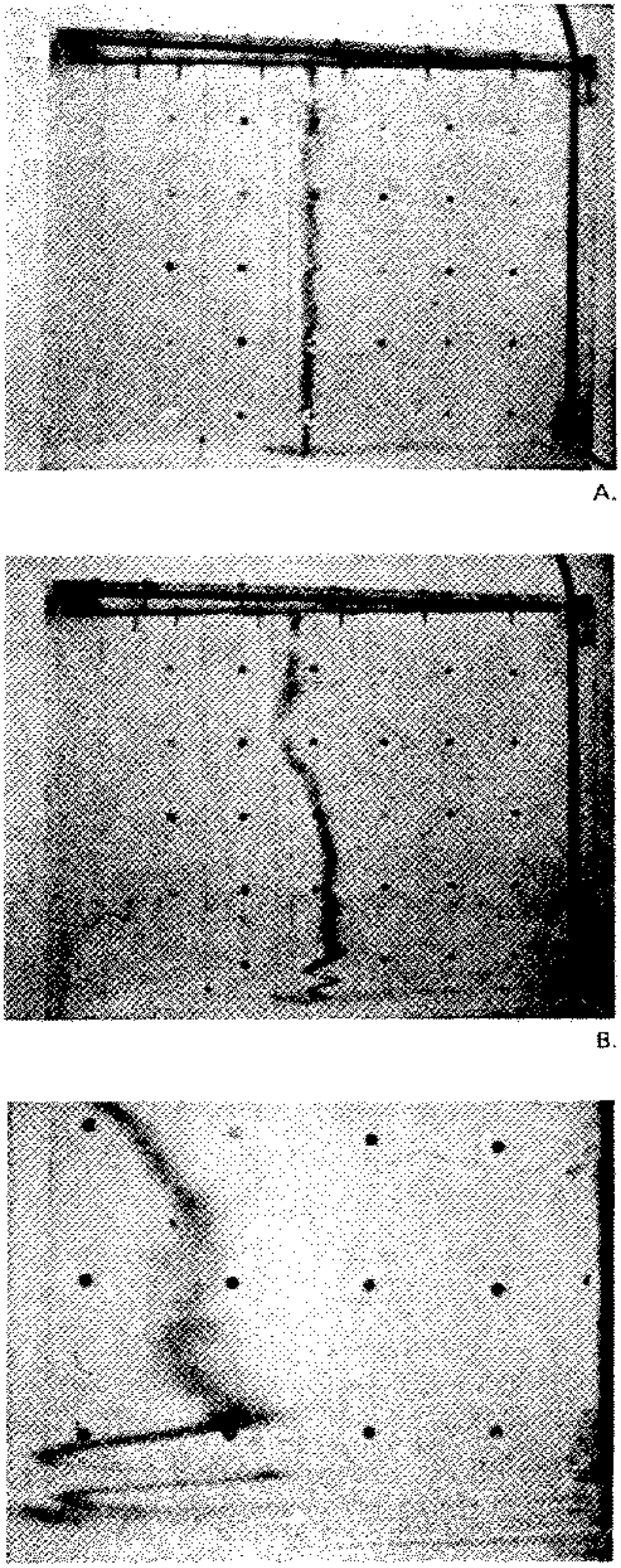


Figure 8. Column of dyed fluid in a nonuniform ambient brine. (a) the column of colored fluid; (b) deformation of the column after 10 min. of water injection, and (c) location of peaks with respect to the inlet.

profile in the ascending fluid by conventional measurement methods was impossible:

1. The thickness of the ascending fluid layer; it was estimated to vary from .5 mm to 5 mm for the injection rates used.
2. The way the wedge shape model was constructed; it made the rising fluid rather inaccessible.

Some qualitative studies regarding the salinity profile in the rising fluid were made by conducting mixing experiment in stratified brine.

Experiment No. 6

The model was filled with 5 layers of known, high concentration brine (Fig. 9). First the lightest brine was poured into the model; then the next heavier brine was introduced at the bottom of the model through a small pipe. The heavier brine underlayed the lighter one. This was done slowly and carefully in order to get sharp boundaries between layers. The process was repeated for the remaining three layers.

The rate of injection was 1 cc/min. and mixing was traced visually by addition of dye to the injection water. The rising fluid came to rest in four portions. The continu-

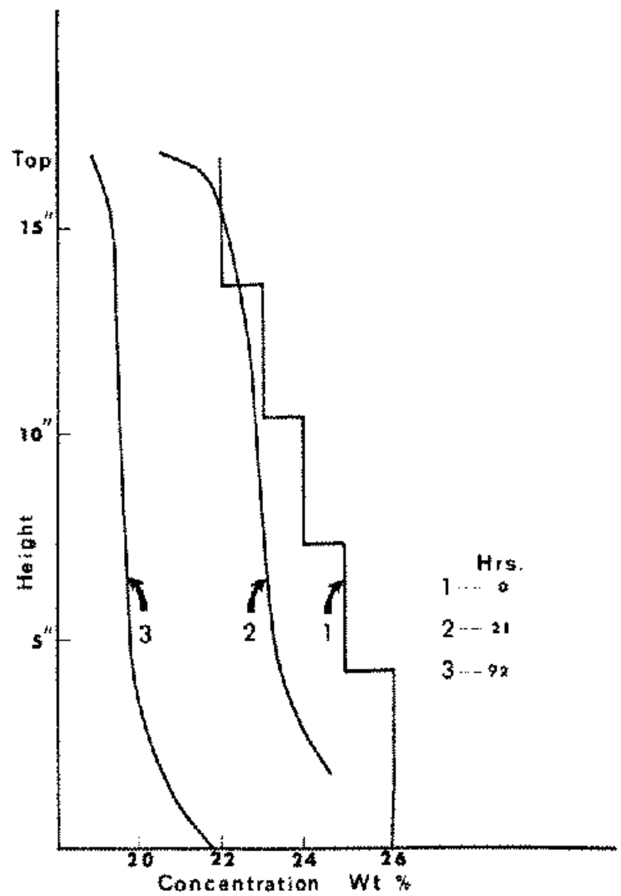


Figure 9. Change of concentration in high salinity stratified brine.

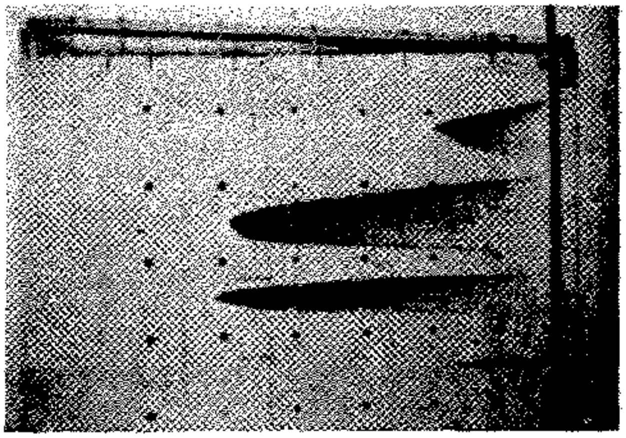


Figure 10. Formation of four bands of mixed fluid in stratified brine.

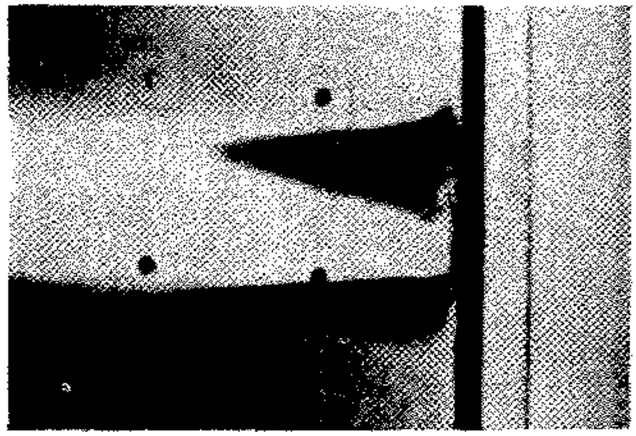


Figure 11. Formation of two bands of mixed fluid at the boundaries between the 4th, 3rd, and 3rd, 2nd brine layers.

ation of this process developed four bands of mixed fluid shown in Figure 10. The smoothing out of the concentration profile of the bulk fluid from a steplike to a continuous shape due to water circulation is indicated in Figure 9.

Experiment No. 7

The model was filled with 5 layers of brine of known, low salinity. Two of the layers were colored for easier observation of the stratification. Water was injected at the rate of 1 cc/min. A different color dye was added to the injection water to trace mixing. A segment of the rising fluid came to rest passing the boundary between the fourth and third layer. The remainder of the ascending fluid came to rest at the boundary of the third and second layer. The continued process developed two bands of mixed fluid shown in Figure 11. The changes in bulk fluid concentration profile due to water circulation and also a pronounced diffusion action are shown in Figure 12. As the bulk fluid salinity profile after 284 hours of water injection indicates the salinity of the first (top) layer has increased. Up to that time the first layer was unaffected by water circulation and its salinity buildup could only be attributed to diffusion from the second layer.

MIXING IN THE PRESENCE OF A DISSOLVING BOUNDARY

In order to simulate a segment of a cylindrical salt cavity a 4½" thick salt slab was fitted into the model on the side opposite the axis.

Experiment No. 8

The model was filled with saturated brine. Water injection was started and the rate of brine production was set at 1 cc/min. After 18 hours the brine concentration practically stabilized. This time was taken as zero time. Dye was introduced to the injection water. After 125 hours the run was terminated (143 hrs. total). Table I lists the concentration of the bulk fluid at zero time and at the end of

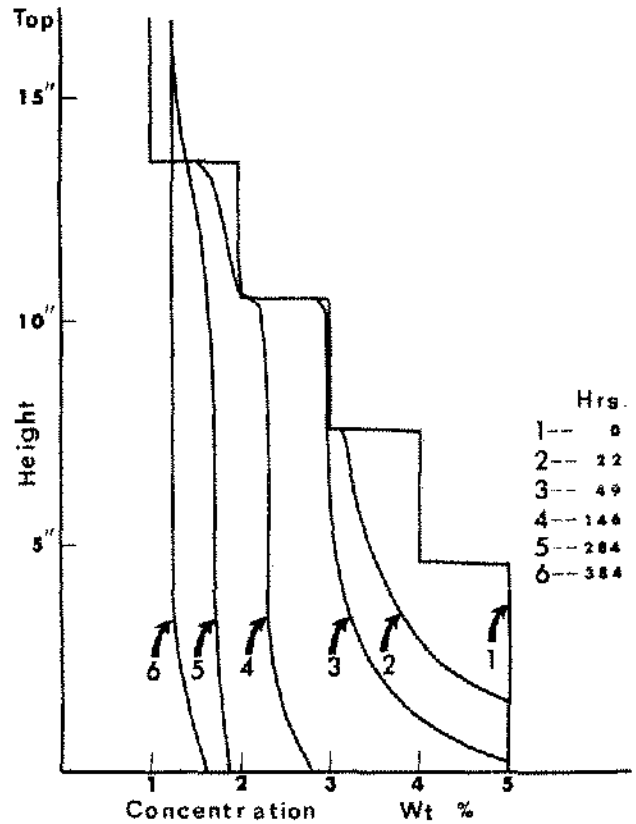
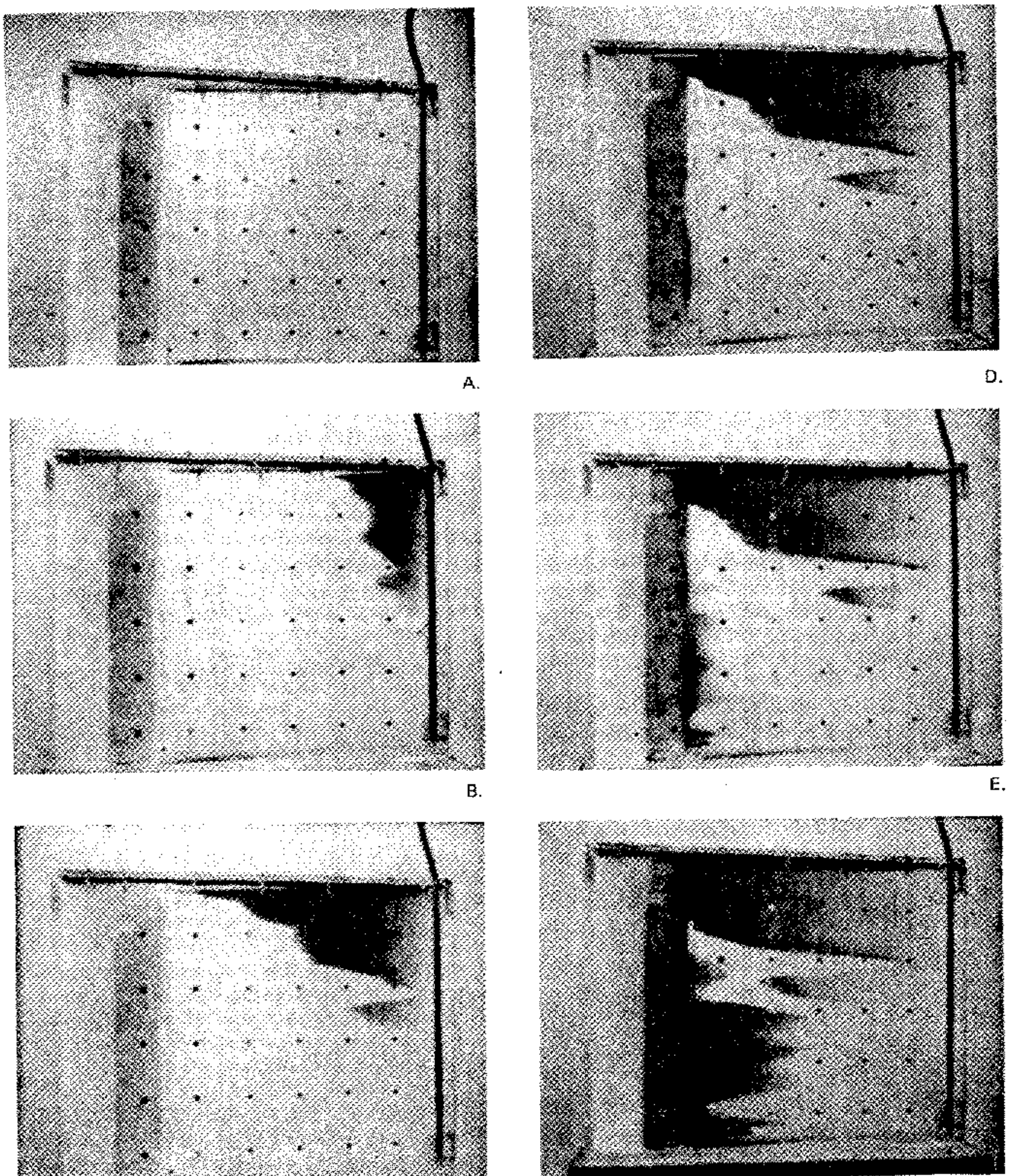


Figure 12. Change in concentration in low salinity stratified brine.

TABLE I

Height Inches	wt % Time = 0	Concentration Time = 125 hrs.
15¾	24.99	24.88
14	25.34	25.34
11	25.45	25.45
8	25.57	25.57
5	25.68	25.62
2	26.14	26.03
¼	26.14	26.14



A. D. B. E. C. F.

Figure 13. Process of mixing and dissolution in saturated brine. (B) mixed fluid envelope after 5 min.; (C) after 40 min.; (D) descent of colored fluid along the salt surface at 100 min.; (E) progression of mixing and dissolution at 115 min.; (F) progression of mixing and dissolution at 180 min.

the experiment. The closeness of these values appear to justify the assumption of a constant salinity profile in the bulk fluid.

Figures 13 a–f illustrate the process of mixing and dissolution. The envelope of mixed fluid moving away from the axis faced the opposite movement due to salt dissolution in the top portion of the model. The co-existence of these opposing movements is indicated by the fingering in the mixed fluid. (Compare Figures 13b and 6.) In the lower part of the model no such counter flow existed. The bulk fluid moved in one direction away from the salt toward the pipe.

CONCLUSIONS

1. The extent of mixing based on the volume of brine entrained per volume injected is dependent on:
   a) rate of injection
   b) the ambient brine density which determines the buoyancy force.
   c) the vertical distance that the fluid is allowed to rise freely.

2. For low injection rate, the rise of water in brine starts with a laminar flow with practically no mixing. Later in the course of ascend the flow becomes totally turbulent. In the transition zone 3 layers within the ascending fluid are suggested: A turbulent core, a buffer layer and a laminar sublayer.

3. The concentration gradient within the ascending fluid rising in uniform concentration brine gradually lessens as the fluid rises. In the case of stably stratified ambient brine the variation of the concentration profile in the ascending fluid is governed by the gradient in the ambient brine.

4. The dissolution of salt induces motion in the ambient fluid which affect the rise of water; this in turn affects the dissolution process. The effect of mixing on dissolution and vice versa is more pronounced when the brine medium separating the two systems of transfer is limited in extent. In other words the mixing affects the salt dissolution to a greater extent in the earlier stages of salt cavity washing.

5. This experimental investigation has shed some light on the convective mixing of water with brine in salt cavities and its effect on salt dissolution. Some of the information provided should be useful in efforts of predicting cavity shapes and concentration of the produced brine by numerical simulation or other methods.

ACKNOWLEDGMENTS

The material presented in this paper is based on the M.S. Thesis by A. Saberian, presented to the Department of Petroleum Engineering, the University of Texas at Austin, August, 1971. The authors wish to thank the Solution Mining Research Institute, Inc., Floosmoor, Illinois, for a grant under which this research was carried out. Special recognition is due to the late Dr. Frank W. Jessen, who supervised the project.

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