Densimetric exchange flow in rectangular channels

II.—SOME OBSERVATIONS OF THE STRUCTURE OF LOCK EXCHANGE FLOW

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This second paper of the series describes how greater understanding of the varying mechanisms of exchange flow was obtained from relatively simple experiments involving the colouring of 'blocks' of water before the start of an experiment. It became apparent that capacity for the fronts of an exchange flow of large densimetric Froude-Reynolds number to maintain almost the initial velocity for considerable relative distance (i.e. for a travel distance of many times the depth) depended on the continual discardment of the diluted water at the front and its replacement by more or less undiluted water which overtook the front. Although with decreasing densimetric Froude-Reynolds number the rate of entrainment at the fronts decreased, the rate of discardment decreased more rapidly and the velocity of the fronts diminished in a relatively shorter distance. At very small densimetric Froude-Reynolds numbers when the flow was basically laminar, dilution of the fronts became the dominant factor in the lock exchange flow phenomenon.

Attempts to obtain recordings of the velocity and dilution structure were only moderately successful in illustrating the effects of variation of scale because of the combined limitations imposed by the size of the flumes used and by the recording techniques available. However, taken together with some previous observations, and with observations made of dye streaks injected into the moving bodies of water—a modification of the original block colouring method—the combined evidence is considered to be sufficient to support the contentions.

1. INTRODUCTION

In the first page under the general title of the series (Barr, 1963) which will be referred to as I, various pure density current cases of densimetric exchange flow in water were listed, and information on their overall characteristics was given. It was demonstrated that the scale of such phenomena should be determined on the basis of the densimetric Froude-Reynolds number. Details were given of the velocities of the fronts, both in respect of changes in the coeffi-

cient of proportionality with variation of scale and between different types of front and also in respect of the pattern of diminution of velocity of a front. Using this knowledge, a design method for hydraulic model studies involving densimetric spread had been devised. This showed that the practical relevance of the idealised two dimensional exchange or spread studies was not confined to the understanding of small density difference effects in canal and lock systems and the like, but extended to the much more common occurrence of the three dimensional spread of a buoyant discharge. It

was said in I that the next stage in the programme of study of exchange flow should be to attempt to learn more of the structure—the internal velocities and the dilution patterns. This paper is concerned with such observations.

2. NOTATIONS (as used in I)

- B is the breadth of the rectangular flume;
H is the primary characteristic vertical distance; in the case of lock exchange flow the depth;
L is a length along the flume—measured from the removeable barrier;
 L_0 is the distance from the removeable barrier to the fixed barrier in the case of a "short" lock.
V is the velocity of a front after some extension;
 V_0 is the initial velocity of a front immediately after the removeable barrier is lifted;
 $\Delta\rho/\rho$ is the non-dimensional density difference or the density difference ratio; $\Delta\rho = \rho_1 - \rho_2$ where ρ_1 and ρ_2 are the densities of the two bodies of liquid; and it is assumed $\rho_1 \neq \rho_2$;
 V_Δ is $[(\Delta\rho/\rho) \cdot g \cdot H]^{1/2}$ or the characteristic velocity such that the densimetric Froude number ($\mathcal{F}_\Delta$) equals one;
 $\mathcal{F}_\Delta = V_0/[(\Delta\rho/\rho) \cdot g \cdot H]^{1/2}$, where V_0 is a characteristic velocity;
K is the ratio V_0/V_Δ ;
 $\overline{\mathcal{F}_\Delta \mathcal{R}}$ is the densimetric Froude-Reynolds number $[(\Delta\rho/\rho) g^{1/2} H^{3/2}/\nu]$, where ν is the kinematic viscosity (see I for the limitations on this number).

3. SOME FURTHER DETAILS OF PREVIOUS LOCK EXCHANGE EXPERIMENTS

Before the present programme of studies was initiated at the Royal College of Science and Technology, Glasgow, attention had been, in general, directed towards the underflow. It was therefore usually found convenient to colour the more dense water in its original position and thus see clearly the progress of the underflow after the removal of the barrier. To the eye, and to the camera, the coloured water is dominant over uncoloured water. The dilution of the progressing underflow can be quite advanced before it is visually obvious. On the other hand if an

uncoloured front progresses into coloured water its form may be difficult to distinguish because of the coloured water which is drawn into its swirling tip. By colouring first the more dense and then the less dense water and taking sets of simultaneous photographs at selected stages of development of the exchange flow in both cases, Keulegan (1957) built up a composite picture of exchange flow for one chosen case. His configuration, influenced by an interest in the motion of salt water released into a canal from a short lock (length L_0) was $B/H = 0.5$, $L_0/H = 7$, and there was sufficient canal length for L/H for the underflow to reach 40. With $H = 10$ inches, $\Delta\rho/\rho = 0.020$, $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$ was 23,800. Although the latter stages of development were naturally much affected by the reflection (Fig. 1) resulting from the overflow striking the end of the lock the early recordings from these experiments first demonstrated that the development of the overflow and underflow in free surface lock exchange flow are not symmetrical. Barr (1959) studied both overflow and underflow and found as shown on Figures 1, 2 and 4 of I that the initial tip velocity of the overflow exceeded that of the underflow by about 12 % throughout the range of $\overline{\mathcal{F}_\Delta \mathcal{R}}$ attainable in a moderately sized flume. No measurements of water velocities were made by Keulegan or Barr, nor have such been reported for controlled conditions by any other workers, so far as is known (Allen and Price, 1959, have compared some velocity measurements for a complex and unsymmetrically non-prismatic prototype configuration and a model thereof). Indeed the total colouring of one or other of the bodies of water to allow easy observation of the tip velocities has tended to prevent any visual impression of the internal velocities being obtained. Prandtl (1952) has indicated that

FIG. 1

Diagrammatic illustration of reflection effects in lock exchange flow-overflow reflected.

Représentation schématique des phénomènes de réflexion intéressant un écoulement d'échange en écluse, avec réflexion de l'écoulement « par en-dessus ».

follow-up velocities approaching twice the frontal velocity may occur in analogous cold-warm air phenomena (truly analogous to dam burst analogy exchange flow).

As regards mixing actions, two type were noted. At the tip, especially the underflow tip, there was a rolling up process similar to that shown in Prandtl's (1952) illustrations. This was observed when the interface was otherwise completely smooth, suggesting practically laminar conditions of flow at the interface at least. In some cases the spiral was seen quite as distinctly as in Prandtl's idealised figure (Barr, 1959). As the increasing of the depth or of initial density difference, or both, led towards more turbulent conditions, the spiralling layers no longer appeared to have distinct existence, but the general pattern of movement seemed to be the same.

The other type of mixing action which was clearly observed, occurred behind the tip of the underflow when the depth and density difference were such as to give values of $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$ of the order of 5,000 or rather less. Interfacial waves, on the point of breaking, were observed in the region behind the underflow front in exchange flows of the order of 3 inches total depth in an 18 inch wide flume and when the extension to depth ratio of the front, L/H , was of the order of 20 to 30. When $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$ was slightly increased, breaking of the waves could be seen and on further increase the individual waves could no longer be distinguished, the general impression gained by the first author after watching many experiments, being that the turbulent mixing between the two layer grew more intense with increasing values of $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$.

The appearance of the two conditions of non-breaking and just breaking waves was very similar to the photographs given by Ippen and Harleman (1952) for a similar, though steady state, circumstance. This type of interfacial wave formation was also noted by Ellison and Turner (1959) as occurring behind the nose of an underflow layer progressing down a slight slope.

It seemed reasonable to assume that similar waves could be obtained behind an overflow front, though such were not actually observed.

Thus the overall impression at the end of the first stage of the investigation of lock exchange flows was that the two mixing actions, particularly the second, intensified with increasing values of $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$ and that interfacial drag provided the explanation for the relatively more pronounced diminution of velocity of low values of $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$. Without any actual measurements

having been taken, the impression of an interface more or less distinct, depending on the degree of turbulence, and with turbulent or laminar type velocity distribution patterns above and below the interface was also present.

4. THE FLUMES (A, B and C)

It is convenient to briefly describe the flumes used for the experiments considered here, and which were used in obtaining the results given in I. Some details pertinent to the next paper (III) are included.

Flume A was built in 1958 at the start of the programme of study of densimetric effects which was then primarily intended to give understanding of the useful scope of heat dissipation models and of the scaling thereof. Thus the flume was planned to serve various functions and was a compromise between the needs of these various functions and the space available.

It was 18 inches wide, 10 inches deep and had a total length of 19 feet. Together with an 18 feet by 7 feet by 18 inches deep tank used for the three dimensional studies mentioned in I, it formed a circuit in which a controlled flow could be obtained by means of a $\frac{3}{4}$ cusec pump, a constant head tank and a V-notch weir installed as part of the circuit. To use the flume for lock exchange flow experiments, a permanent barrier was placed near the "upstream" end and an adjustable gate at the "downstream" end was raised. The position of the grooves for the removeable barrier gave a 13 feet length between it and the end gate. Initially the permanent barrier was placed to give a 4 feet shorter length and latterly a $5\frac{1}{2}$ feet shorter length. This flume, which had one side transparent, is shown in Figures 5 and 6 of I and was always used open, there being no top. It was not, in general, easy to light for photographing or to photograph, part of its length running close to a wall.

At a higher level in the laboratory two batching tanks were served by the normal hot and cold water supplies, and were of sufficient capacity to provide the 17 and 7 cubic feet necessary to fill the larger and shorter lengths respectively. During lock exchange experiments this water was fed into the lengths, separated by the removeable barrier. After a test the water was quickly dumped into the tank by lowering the adjustable gate leaving the flume ready for another test.

Flume B was a $4\frac{1}{8}$ in. by $4\frac{1}{8}$ in square "pipe," again with one side transparent. It was sixteen

feet long, with the removeable barrier in the middle and with solid ends. It was placed on a long table which could be rapidly tilted to aid emptying and filling from the same high level batching tanks as used for flume A. Flume B could be easily photographed, and is shown in Figures 4 and 5 *b* of I.

Flume C was also of the enclosed type, 4 feet long and of $1\frac{1}{2}$ inch by $\frac{1}{4}$ inch section with the removeable barrier in the middle. It could be used as either a "wide" flume with $B/H = 6$ or as a very narrow flume with $B/H = 0.167$.

5. OBSERVATIONAL EXPERIMENTS WITH BLOCK COLOURING (Flume A, 1961)

By introducing one or more additional thin vertical cross barriers into the flume once it had been filled in the normal way for a lock type exchange experiment, it was possible to colour a block of either the more dense or the less dense water without otherwise affecting the experiment. These additional barriers were then slowly withdrawn, leaving the coloured block moderately distinct and soon after this the experiment could be started in the normal way by swiftly lifting the main barrier. This simple technique at once gave a new insight into exchange flow. First a block of the more dense water next to the main barrier was coloured during an experiment of depth and density difference such as to give a low densimetric Froude-Reynolds number ($K \cdot \overline{\mathcal{F}_\Delta} \mathcal{R} = 1,000$). Although upon initiation of the exchange some of the coloured water was distributed along the extending interface most of it moved along the flume with the underflow. Dilution occurred due to the entry of the less dense water just behind the characteristic bulge, but the diluted water mostly remained in the forward part of the underflow. The velocity rapidly diminished and it appeared that the dilution had inhibited the capacity for advance. When a block further back from the main barrier was coloured, no coloured water reached the front during the period of observation which lasted until the frontal velocity had fallen to a small fraction of the initial velocity. Similar experiments were then undertaken with $K \cdot \overline{\mathcal{F}_\Delta} \mathcal{R}$ values of 7,000 upwards for both underflow and overflow. Blocks of water initially some small distance from the main barrier were coloured. When these came into motion most of the coloured water was seen to move rapidly after the front, to overtake it, to be diluted by the pronounced mixing action at the nose, and to be discarded to form an interme-

diate layer between the main stream following (and feeding) the front and the opposing counter flow. This intermediate layer thus served to separate the main forward transfer zone from the necessary counter flow. It is convenient to call the main flow the sub-current, whether it be the underflow or the overflow case, because it is distinguished as being some distance within the boundary of the underflow or overflow as might be defined either by the line joining zero velocity points or the line of equal mixing of the two differing bodies of water.

6. VARIOUS RECORDINGS OF THE STRUCTURE OF LOCK EXCHANGE FLOW

Explanatory note.

The obvious follow up to the block colouring observations made in 1961, seemed to be to obtain measurements of the internal structure of exchange flow—velocities and dilution—as evidence of the varying mechanisms that had been observed. This was in fact attempted with only moderate success. Now as this paper is being prepared in 1963, the somewhat difficult task of internal structure measurements in an unsteady system seems less important for several reasons:

(i) Although three dimensional spread is not really within the scope of these papers, it has been explained in I that the desire to formulate rules for the scaling of hydraulic models involving three dimensional spread was the original motivation of the studies. After the attempts to obtain recordings of the structure in the two dimensional case during 1961, it was decided to apply a modification of the block colouring method to the simplified outfall studies mentioned in I. Here the procedure was extremely simple—the buoyant water discharged from the outfall was coloured with a weak dye. Some time after the start of an experiment when a surface field had formed, a second and dominant colouring agent was added to the outfall flow and the further time interval for the second colour to overtake the spreading front on, say, the produced centre line of the outfall was noted. Various initial intervals were so tested and then the whole repeated at a different horizontal scale (on fifth size with appropriate vertical exaggeration). This proved to be a very useful method of assessing the degree of similarity obtained in internal motions as between small scale idealised outfall configurations using the congruency diagram scaling method, and did

not involve any direct measurement of fluid velocities.

Again, knowing now what to look for, the overtaking and discardment patterns, which must be general to all spread phenomena where the two liquids or fluids are miscible, were easily and reassuringly recognised in the large heat dissipation models being operated by the Civil Engineering Department of the Royal College during 1962 (Smith, 1962).

(ii) It is now known that there are at least two methods of setting up steady state exchange flow; the first of these has already been described (Barr, 1962), the second and more important case is to be dealt with in III. Although the mechanisms of entrainment and discardment may differ in detail in such cases, there must be basic similarity to those mechanisms as they occur in the non-steady cases and certainly recordings would be much simpler to obtain.

For these reasons it was decided (in 1963) merely to obtain, as simply as possible, sufficient additional recordings that the combined evidence would clearly illustrate how variation of the discardment to entrainment ratio affects the diminution of velocity patterns. If, as is hoped, enlarged and improved facilities become available for the study of both non-steady state and steady state exchange flows, it can then be decided to what extent detailed observations of structure are desirable and feasible in the non-steady cases.

Photographs of pairs of experiments with differential colouring.

Keulegan's (1957) use of the technique of differential colouring has already been mentioned, in 3 and Figure 4 of I shows typical results obtained in this way. Despite the short lock length ($L_0/H = 7$) and the narrow flume width ($B/H = 0.5$) Keulegan's results can be held to provide some evidence relevant to the standard case—it cannot be thought for instance that either the narrow width or the effect of a reflection of the overflow from the lock end would at any time increase the velocity of an underflow front. In this case with a $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ value of 23,800, the front velocity (V) at an extension to depth ratio (L/H) of 39.3 was slightly greater than $0.9 V_0$. At all times up to this extension undiluted saline water was found by Keulegan to extend along the bottom of the flume and right up to the very front of the underflow. Above this bottom layer lay a zone of mixed water, typically occupying between one fifth and one sixth of the total depth. It will be seen from Figure 8 of I that the L/H ratio at $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ of about 24,000 for $V/V_0 = 0.9$ is, by

extrapolation, estimated to be about 110, near the "estimated" limit of 120 for the standard case of a wide channel ($B/H \geq 6$) with no reflection.

The comparable limits of L/H (i.e. L/H for $V/V_0 = 0.9$) for the narrow channel ($B/H = 0.5$) as found by Keulegan were about 50 for L_0/H of 7.2 and 65 for L_0/H of 14.4. Data for the standard case at $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ values from 20,000 upwards is very much needed—it is not possible to fully distinguish between the effects of the narrow channel and of the reflection which must obviously combine to reduce the capacity of the underflow to maintain the initial velocity, but the results of Keulegan quoted lead one to expect that for $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ values of 24,000 upwards and presuming the standard case, undiluted water would be present at the front moving at velocity $V > 0.9 V_0$ for L/H values of upwards of 70 and perhaps much greater.

Figure 4 and 5 of I provide roughly comparable information for $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ values of about 5,000. In the case of Figure 4 the L/H value for the overflow was 18 at the time each photograph was taken (i.e. an extension of 6 feet). The extension of the underflow is seen to be about 5 feet 5 inches ($L/H = 16.2$) and $(18-16.2)/16.2$ is about 11 %, very close to the typical 12 % quoted in I. Two trends can be observed: firstly there are signs of dilution at the fronts despite the comparatively small L/H ratios (L/H for Figure 5 a is 3.2 and for Figure 5 b is 11.6); and secondly the zones of mixed water appear to be thinner than in Keulegan's experiment.

For the next two stages of decrease of $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ which are to be described, no attempt has been made to obtain photographs; it was thought that it would be difficult to obtain meaningful results. Further the trends become most pronounced and, because of the great increase in time available for visual observation, easier to describe. The same flume (B) as is shown in Figure 4 of I was filled to 1 inch depth or $\frac{1}{2}$ inch depth ($K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ in the region 200-600). Thus a much greater relative extension was possible than when it was full or nearly full. Figure 8 of I shows how pronounced diminution of velocity occurred at relatively small extensions. It was most noticeable that a coloured front become considerably diluted and that this dilution extended back for some distance; moreover it was now practically impossible to observe an uncoloured front penetrating into a coloured zone beyond the initial stages of development.

The final stage of decrease of $K.\overline{\mathcal{F}}_\Delta\overline{\mathcal{R}}$ was reached in Flume C. This $\frac{1}{4}$ inch deep enclosed flume was constructed entirely of perspex and

the fronts were observed by viewing from above with a white background below. Although the initial $\frac{1}{4}$ inch of potassium permanganate coloured water appeared as a dense colour, the dilution was so pronounced that it became difficult to observe even the coloured front at L/H values of 30 and above. In one experiment ($K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R} = 45.5$) which was continued long after the stage required to obtain data for Figure 8 of I, the front was still just visible at L/H of 62, moving at about 0.005 inches per second ($0.017 V_0$) and with the colour deepening only gradually with distance back towards the barrier. The impression was gained that the mechanism of exchange was completely reversed from that obtaining in the turbulent region. Instead of undiluted water continually overtaking the front—and thus necessitating greater internal velocities than that of the front—the water to the rear appeared to have almost come to rest, with the front maintaining its advance only by completely entraining the water into which it moved.

Dye injection observations.

To obtain some definite results illustrating the entrainment and discardment process a simple dye injection system was arranged for flume B. Experiments were conducted by colouring one of the dissimilar bodies of water with fluorisene and by injecting potassium permanganate solution once the exchange flow had been initiated. Two combinations of depth and of density difference were chosen to be close to the limits of $K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R}$ thought reasonable in the circumstances

	Depth (H)	$\Delta\rho/\rho$	$K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R}$ (assuming $K = 0.5$)
(i)	3 in.	0.032	5,650
(ii)	1 in.	0.005	430

A 0.03 inch bore stainless steel tube was used to inject the dye; one end was blocked and a circular hole of slightly smaller diameter was drilled at right angles to the axis of the tube and just above this end. The tube was inserted into the flume through holes drilled vertically in the top board one inch from the perspex side and was always positioned so that the axis of the outlet hole was normal to the length of the flume.

Considering the experiments with the larger value of $K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R}$ (5,650) first, the injection tube was positioned 9 inches (3 H) in front of the barrier and either half an inch from the bottom or just below the water surface for underflow and overflow respectively. The front was allow-

ed to pass the tube by some predetermined distance then dye was injected and the extension of the tip of the front at the point when the injected dye reached the tip was noted—the point of "overtaking". Results were obtained as shown in Table 1.

TABLE 1
Details of overtaking observations
 $K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R} = 5,650$

TYPE OF FRONT	PASSING DISTANCE		OVERTAKING POINT (distance from tube)	
	Inches	Relative	Inches	Relative
Underflow. .	9	3 H	36	12 H
Underflow. .	18	6 H	69	23 H
Overflow. . .	9	3 H	36	12 H
Overflow. . .	18	6 H	84	28 H

Figure 2 shows photographs taken during an experiment of this type. The fluorisene just shows on the original print and dotted lines have been added to delineate the tip. The numbers indicating feet from the barrier have also been re-touched. In this case the passing distance estimated from Figure 2a was 3.5 H or slightly more and it can be seen that overtaking had occurred by 16 H (c) but that the full density of colour at the tip had not yet been reached. In another set of photographs of an overflow experiment, which were obtained by time lapse cine camera, the passing distance was just over the desired 3 H and the relative distance to the overtaking point was about 13 H—this being in reasonable agreement with the visual observation.

Results for similar experiments at the lower $K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R}$ values (430) were as shown in Table 2, the tube being placed in the same relative position.

TABLE 2
Details of overtaking observations
 $K \cdot \overline{\mathcal{F}}_{\Delta} \mathcal{R} = 430$

TYPE OF FRONT	PASSING DISTANCE		OVERTAKING POINT (distance from tube)	
	Inches	Relative	Inches	Relative
Underflow. .	3	3 H	15	15 H
Underflow. .	6	6 H	45	45 H
Overflow. . .	6	6 H	45	45 H

(a)

Just after start of injection-front well ahead.

Juste après le début de l'injection.

Le « front » précède de beaucoup le débit coloré.

(c)

Dye has reached front, but not a full intensity.

Le débit coloré a rattrapé le « front ».

mais le colorant n'a pas encore atteint sa pleine intensité.

(b)

Dye stream in the process of overtaking.

Débit coloré rattrapant le « front ».

(d)

Intensity of dye at front building-up.

Augmentation de l'intensité du colorant au front.

FIG. 2

Views of dye injection experiment. (The figures indicate distance in feet from the barrier.)

Essai avec injection de colorant. (Les chiffres visibles sur les photos donnent la distance, en pieds, à partir de la barrière.)

Although the increase in relative distance in the first of these observations was slight compared with the corresponding experiment in the more turbulent range, it appeared that the use of the same tube with the same intensity of spurt of dye into the much shallower and more slowly moving front tended to introduce an error. The second and third observations do show a marked divergence from the corresponding tests in the previous set, and in all cases, it was noted that when the dye did reach the front it was considerably more diluted than previously. The impression of a definite overtaking place was certainly lost.

Internal velocity measurements (Flume A, 1961).

A miniature current meter of the type developed by the Hydraulic Research Station (Dedow and King, 1954) was available and it seemed

worth while to attempt to use it for velocity measurements. The instrument was capable of recording velocities down to about 1 inch per second. Although front velocities much greater than this could be obtained in the flume using a saline density difference, this was not found practicable. The count of revolutions of the tiny rotor (1 cm) depends on passage of current through the water.

Provision is made for balancing the circuit with fresh or salt water, but difficulty was experienced with the changing concentration at the rotor. The maintenance in balance was found to be much easier when thermal density difference was employed, though this meant that the instrument was always used very near to the lower limit of effective measurement.

The count of rotor revolutions shown on the decatron display can be either continuous or intermittent (i.e. the count lasting 10 sec. is made

FIG. 3
Typical results of velocity measurement
with miniature current meter, $K \cdot \overline{F}_\Delta \cdot \overline{R}$ about 10,640,
rotor 6 ft. from removeable barrier.

Résultats typiques de mesures de vitesses au micro-moulinet, avec $K \cdot \overline{F}_\Delta \cdot \overline{R}$ égal à environ 10 640, le rotor du moulinet étant à environ 1 pied de la barrière amovible.

every other 10 sec.). Because of the unsteady nature of lock exchange flow and the relatively short duration of any experiment, the intermittent setting was discarded on the ground that half the potential velocity measurements would be missed. Two longitudinal positions were chosen for the rotor, at 1 foot and 6 feet from the barrier, and the rotor axis was set parallel to the centre line of the flume bottom at 0.16 feet from the bottom and 0.16 feet below water surface for measurements of underflows and overflows respectively, the total depth being made 0.8 feet, throughout. At the start of an experiment a stop clock with a circular paper disk stuck to the face was also started and the times corresponding to the first indication of

FIG. 4
Typical results of velocity measurement
with miniature current meter, $K \cdot \overline{F}_\Delta \cdot \overline{R}$ about 8,420,
rotor 6 ft. from removeable barrier.

Résultats typiques de mesures de vitesses au micro-moulinet, avec $K \cdot \overline{F}_\Delta \cdot \overline{R}$ égal à environ 8 420, rotor à 6 pieds de la barrière amovible.

movement and then successive counts of 10 pulses were marked on the desk by ticking the position of the hand. The method thus tended to give individual errors but eliminate cumulative error. Figures 3 and 4 show typical results; whether at 1 foot or 6 feet from the barrier or for overflow or underflow, it was always found that the mean velocity indicated was greater than the initial front velocity — which did not in fact diminish greatly within the flume length at the $K \cdot \overline{F}_\Delta \cdot \overline{R}$ values of about 10,000.

To obtain roughly comparable measurements at small values of $K \cdot \overline{F}_\Delta \cdot \overline{R}$ with velocities below the 1 inch per second minimum of the current meter, dye splotches were released some short distance behind the overflow front soon after withdrawal of the barrier. Typical results, showing comparison of front travel with that of the foremost point of the dye trace are given on Figure 5. There was certainly much less sign of overtaking during these tests at $K \cdot \overline{F}_\Delta \cdot \overline{R}$ values about 2,400, than during the previously described tests at $K \cdot \overline{F}_\Delta \cdot \overline{R}$ values about 10,000.

FIG. 5
Typical results of velocity measurement by observation
of dye splotch, $K \cdot \overline{F}_\Delta \cdot \overline{R}$ about 2,400.

Résultats typiques de mesures de vitesses par observation d'une tache de colorant, avec $K \cdot \overline{F}_\Delta \cdot \overline{R}$ égal à environ 2 400.

Attempts at dilution measurement.

The difficulties involved in the measurement of dilution in an unsteady turbulent system are not inconsiderable, and have not been overcome in this case. What seemed desirable was to obtain simultaneous vertical traverses at a range of points along developing exchange flows. A recording system based on thermopile probes with oscillograph recording had been developed (Barr, 1962) and successfully used (Barr, 1963 A) in a steady state mixing study. If the system was used with the four thermo-junctions protruding from the measuring end of each $\frac{1}{8}$ in. diam. probe uncovered, localised measurements (to

within an $\frac{1}{8}$ in. cube roughly) could be obtained of the turbulent fluctuations in a mixing zone of warmer and cooler bodies of water. By forming a blob of wax over the measuring end, the speed of response was very much reduced and the time average temperature at a point in a mixing zone could be found if the system were steady state. Records from eight measuring points could be obtained in one second. But even the availability of a moderately sophisticated recording system such as this was not really helpful. The superimposition of short period turbulence transients on longer period transients caused by the rapidly changing state of development of the exchange flow made both conditions of the probe ends unsuitable. What was done was to attempt to isolate vertical samples by placing $1\frac{1}{2}$ inch diameter perspex tubes into the flume during an experiment and then making a vertical traverse with an angled bulb thermometer lowered vertically into the tubes using a ratchet mechanism which incorporated a depth scale. The method was not very satisfactory; some additional mixing often took place during or immediately after the placing of the tube, although the records from the subsequent downwards then upwards traverses were fairly consistent. The only definite conclusion that could be drawn from the results (Hassan, 1962) was that the net transport of water in a underflow where $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$ was in the region of 10,000 was observably greater than in a corresponding development of underflow with $K \cdot \overline{\mathcal{F}_\Delta \mathcal{R}}$ about 2,000; especially in the region near the tip.

7. DAM-BURST ANALOGY EXCHANGE FLOW

This case of pure density exchange flow was defined in I and some assessments of the coefficient of proportionality for the initial velocity of both the underflow and overflow were given. A few "block" colouring experiments were carried out for this case and it was found that, as would be expected, the same overtaking, entrainment and discardment process took place at the fronts as had been observed in lock exchange flow.

8. CONCLUSIONS

It has been shown that the mechanism of lock exchange flow changes considerably with change of scale—scale being measured in terms of the $\overline{\mathcal{F}_\Delta \mathcal{R}}$ number. At very small scales the extension of the fronts is rapidly inhibited by the build up of diluted water at the front. With

increasing scale the stage is reached well with the laboratory order of size when a discardment process allows the exchange to continue to very much greater relative extensions. Exchange flow in such circumstances—the circumstances presumably of all full size occurrences—is not a two layer system but a three layer system. During the early stages the intense mixing action at the fronts does not cause diminution of velocity. Of course diminution of velocity of the fronts eventually does occur. It seems a not unreasonable hypothesis that this results both from mounting frictional drag and because the "sub-currents" will start to entrain water from the intermediate zone. Thus a front's progress may eventually be inhibited not by the immediate dilution due to the frontal mixing action but because more and more of the diluted water, though initially discarded, returns to the front in the "sub-flow". This trend has been observed in steady state exchange experiments in the laboratory, where the relative extension is comparatively small and to a much greater extent in the field where with the much greater relative extensions possible, there is more opportunity for the gradual entrainment of already diluted water from the intermediate layer.

It appears that the formation of waves on the interface behind a front as observed by Ippen and Harleman (1952), Ellison and Turner (1959) and Barr (1959) is together with the next stage of the breaking of the waves, a transitory stage in the development from laminar to turbulent conditions. The formation of considerable layers of intermediate water above the extending main flows at large values of $\overline{\mathcal{F}_\Delta \mathcal{R}}$ results from discardment of water from the fronts, and not from the intensification of the aforesaid wave action.

The stage has been reached where experiments of a much larger scale than so far possible are required: in particular the extension of the congruency diagram for the standard case of lock exchange underflow and the formation of a diagram for the overflow is a pressing need. It is thought that measurements of structure of exchange flow should now be attempted for the steady state cases, before a return is made to the more difficult experimental problem of the non-steady cases.

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The experiments described in 5 and 6 (d) and (e) were performed by the second author under the direction of the first.

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RÉSUMÉ

Courants de densité en canal rectangulaire

II. — QUELQUES EXPÉRIENCES SUR LA STRUCTURE DE L'ÉCOULEMENT CONSÉCUTIF A L'OUVERTURE D'UNE VANNE

PAR D. I. H. BARR ET A. M. M. HASSAN

Cet article, le second de la série, considère le cas de la figure 1 a de l'article précédent. Au moyen d'expériences simples (en particulier la coloration de masses d'eau bien délimitées au départ), une connaissance plus approfondie du mécanisme de l'écoulement des fronts d'onde (*under-flow* ou *overflow*) a pu être obtenue, qui explique assez bien l'influence du nombre de Froude-Reynolds densimétrique sur la vitesse de propagation du front. Aux faibles valeurs de ce nombre, l'eau mélangée qui se produit au front y reste et diminue la vitesse de propagation. Aux valeurs élevées de ce nombre, l'eau mélangée se répand à l'aval du front et forme une troisième couche de densité intermédiaire, si bien que, l'eau du front étant constamment renouvelée à partir du corps de l'écoulement, la vitesse de propagation du front diminue beaucoup moins vite.

Les tableaux 1 et 2 et la figure 2 illustrent ce phénomène. Une injection de colorant est pratiquée dans l'écoulement, en un point situé à quelque distance de la barrière (3 H dans le cas étudié), un peu après le passage du front (celui-ci a dépassé le tube d'injection d'une distance que les auteurs appellent « passing distance »). Le colorant rejoint le front d'onde lorsque celui-ci est arrivé au point appelé « overtaking point », dont la distance au tube d'injection est donnée dans les tableaux.

Des mesures de vitesses au point fixe, dans le corps de l'écoulement, confirment les observations visuelles. Les figures 3 et 4 portent en abscisse le temps (compté à partir de l'ouverture de la barrière) et en ordonnée la vitesse mesurée en un point situé à une certaine distance de la barrière (0,30 m pour la figure 3, 1,80 m pour la figure 4). La vitesse, plus grande que celle du front, indique bien une réalimentation de celui-ci.

La figure 5 correspond à une faible valeur de $K \frac{\overline{\mathcal{F}}_{\Delta} \overline{\mathcal{R}}}{\Delta}$. On voit en ordonnée, en fonction du temps, la position du front et celle d'une tache de colorant qui ne semble pas devoir le rattraper.

Les auteurs concluent à la nécessité d'expériences à plus grande échelle, en particulier l'extension du diagramme de la figure 8 de l'article I pour les grandes valeurs de $K \frac{\overline{\mathcal{F}}_{\Delta} \overline{\mathcal{R}}}{\Delta}$.