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NACA RM E55L14a



RESEARCH MEMORANDUM

VISUAL STUDY OF FREE CONVECTION IN A NARROW
VERTICAL ENCLOSURE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

February 16, 1956

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VISUAL STUDY OF FREE CONVECTION IN A NARROW VERTICAL ENCLOSURE

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SUMMARY

The free-convection flow of water in a narrow vertical enclosure, cooled at the top through a copper surface and open at the bottom to a heated reservoir, has been studied by means of a shadowgraph. It was found that there is no flow pattern which is steady with time, that is, no region of the enclosure is permanently a region of upflow or of downflow. Because of variations in the size of the various upflow and downflow regions arranged along the length of the enclosure at a given time, and because of changes with time, neither upflow regions nor downflow regions could be characterized by a definite size. The number of upflow and downflow regions varied with time.

The dominating characteristics of the flow patterns were instability and change.

INTRODUCTION

An experiment on free convection of liquid sodium in a thin annulus of large mean diameter has been reported in reference 1. The annulus, which was oriented with its axis vertical, was closed at the top by a surface through which heat was extracted. The bottom of the annulus was open to a reservoir of heated liquid sodium. Temperature measurements were taken around the periphery of the annulus. From these data the existence of alternate regions of "upflow" and downflow, arranged in a regular way around the circumference, was inferred. Not only could it be inferred that the alternate upflow and downflow regions were uniform in size, but also that the flow pattern, once established, did not change. That is, downflow regions always remained as downflow regions and upflow regions always remained as upflow regions.

The present investigation was undertaken to determine by visual observation the details of the flow in a system similar to the one described above. In order to obtain an apparatus suited for flow visualization by optical techniques, a number of departures from the system of reference 1 were required. A rectangular enclosure was used instead of

an annulus. However, the basic situation of heat extraction through a surface at the top and free exchange with a heated reservoir at the bottom was maintained. Distilled water was used as the working fluid rather than liquid sodium.

The extraction of heat at the top surface of the enclosure (or annulus) gives rise to a layer of fluid, in the region of the top, which is relatively heavier than the warmer fluid below. The heavier fluid, when accumulated in sufficient quantity near the top, will push its way downward through the enclosure. The warmer, lighter fluid will rise to take the place of the descending cool fluid. So, regions of upflow and downflow are established. The details of the flow to be determined from a visual inspection are (1) the steadiness of the flow patterns with time, (2) the size and uniformity of the various upflow and downflow regions, and (3) the direction of flow velocities with particular attention to nonvertical components. Further, the visual observation provides an insight into both the initiation and the breakdown of a particular flow pattern.

APPARATUS

The description of the experimental apparatus will be augmented by the photographs of figure 1. An oblique view showing an over-all view of the experimental apparatus is shown in figure 1(a). A front view of the test section on which the important components have been labeled is shown in figure 1(b).

The vertical enclosure, in which free-convection flow patterns were observed, had front and rear walls made of sheets of Plexiglas. The top wall of the enclosure was a solid strip of copper; the end walls were made of Plexiglas strips. The enclosure, which was open at the bottom, was joined to a reservoir of heated fluid. The vertical enclosure was $9\frac{1}{2}$ inches high, 44 inches long, and $\frac{3}{16}$ inch thick. The ratio of height to thickness was therefore about 50 to 1.

Heat was extracted from the fluid at the top of the enclosure through the copper wall that was soldered to a duct through which cooling water was passed. The fluid in the reservoir at the bottom was heated by three tubes that ran the length of the reservoir through which hot water was passed. During the operation of the apparatus, both the reservoir and the enclosure were completely filled with distilled water. Because of the free-convection motion, there was a continual exchange of fluid between the reservoir and the enclosure.

The apparatus was operated for several hours before observations were made in order to insure the disappearance of initial transients.

Flow patterns were studied for temperature differences between the reservoir and the copper strip at the top of the enclosure in the range from 50° to 85° F.

INSTRUMENTATION

The motion of the fluid was viewed by means of a shadowgraph. A point source of light was placed in front of the enclosure as shown in figure 1. Light rays passed through the front wall, the 3/16-inch gap thickness, and the rear wall of the enclosure. The shadow pattern was viewed on a screen behind the apparatus. The shadowgraph picture was, therefore, a two-dimensional picture, which provided information on flow patterns in a plane parallel to the front (or rear) wall. No information could be obtained about flow normal to front and rear walls.

The strongest delineation of the shadow lines occurs where the density gradients change most rapidly. The temperature and density of the hot fluid rising from the reservoir is fairly uniform. Hence, little evidence of the rising stream is seen except where it contacts the cooler, denser fluid. On the other hand, the cooling at the top of the enclosure creates nonuniformities in temperature and, hence, variations in density gradient are induced. The moving shadow lines, which are observed in the shadowgraph picture are associated with density gradients which are carried along with the movement of the cooled, heavier fluid. A photograph of a shadowgraph will not show the motion of the shadow lines, only their instantaneous location. In interpreting the photographs of shadowgraphs (section Shadowgraph Photographs), the presence of the shadow lines in a region of a photograph should be taken as inferring motion of cooled, heavier fluid in the region:

Thermocouples were installed in the front and rear walls of the enclosure to provide supplementary information about the flow pattern. The thermocouple tips were 1/32 inch from the surface of the enclosure. This was the minimum distance at which thermocouples could be installed without giving rise to bumps on the wall of the enclosure.

Shadowgraph Photographs

Photographs of some shadowgraphs are shown in figure 2. The dynamics of the flow, which cannot be learned from photographs, will be discussed in the Flow Dynamics section using the information obtained from long-time observation of the flow.

The eight photographs shown in figure 3(a) cover an area $6\frac{1}{4}$ inches high by 5 inches wide located about one-half the length of the enclosure.

These photographs were taken over a period of several minutes. The cooling surface at the top of the enclosure appears at the top of each photograph. A rather wide variety of flows are in evidence from these photographs. For example, one photograph shows a well-developed downflow, another shows an upflow (i.e., no downflow). Others show downflows in various stages of development (i.e., downflows penetrating into upflow regions and vice versa). Also, upflows and downflows existing side by side are apparent.

The eight photographs shown in figure 2(b) were taken about 1/4 the length of the enclosure from the left end (as viewed from the front). These pictures show the same variety of flow as has already been noted in figure 2(a).

The conclusion that can be drawn from the photographs and from the more revealing long-time observation of the flow, is that there is no flow pattern which is steady with time. That is, no region of the apparatus is permanently a region of upflow or of downflow.

A second finding, which can only be hinted at by photographs, and which is derived mainly from long-time observation, is that the size of an upflow region or of a downflow region is strongly variable. In other words, at a given time, the various upflow and downflow regions existing within the enclosure all generally covered different lengths of the enclosure. With the passing of time, as the flow pattern changed, the newly emerging upflow and downflow regions were generally different in size from their predecessors and also differed in size among themselves. So, there was no particular size characterizing either an upflow or a downflow region. In accordance with this observation, the number of upflow and downflow regions varied considerably with the passage of time.

From observation of the flow during the period of formation or breakdown of the downflow regions, there was considerable nonvertical, sidewise¹ motion throughout most of the height of the region in which the flow pattern was changing. When a downflow was well established, strong sidewise motions were primarily confined to the top of the region of the downflow, although even a well-established downflow often did not fall in a directly vertical line.

Flow Dynamics

The following description of the flow dynamics is based on long-time observation of the flow.

¹Sidewise motion means motion in the direction of the length of the enclosure.

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The cooling of fluid at the top of the enclosure gives rise to a continuous generation of relatively heavy fluid. Heavy fluid generated above an upflow region which is located near a downflow region may move sidewise along the top of the enclosure until it reaches the downflow region. When it reaches the downflow region, the sidewise-moving fluid is turned in an almost vertical direction. A downflow fed by fluid entering it in this fashion is funnel-shaped in appearance; and the downflow region may be regarded as a funnel through which the heavy fluid generated in a given region escapes from the top surface. Heavy fluid generated above an upflow region that is farther from a downflow region may also feed into the nearest downflow region. However, the amount of heavy fluid accumulated during the longer path of sidewise flow may often be sufficient to push downward. In this circumstance, the sidewise motion of the heavy fluid to the nearest downflow region takes place in a band (several inches in height) below the top of enclosure, as well as at the top itself. Of course, these descriptions are generalizations. Sometimes the strength of the upflow is sufficient to confine sidewise moving fluid, generated above a region of upflow, to a small layer near the top of the enclosure, even though the sidewise movement may be over a relatively long path. Alternately, some "chunks" of heavy fluid carry out a sidewise movement below the top layer even though their path of travel is short.

On some occasions, heavy fluid, generated above an upflow region, does not follow an existing path of descent. (For example, the nearest established downflow may be too far away.) Under these circumstances, the heavy fluid generated continues to accumulate above the upflow region. Finally, chunks of heavy fluid force downward. There are three possible endings to this attempted downward movement. One possibility is that the downward-moving chunks of cooled fluid, reinforced by additional heavy fluid from above and also from adjacent regions, reach the reservoir at the bottom. This initial descent is often accomplished haltingly and with considerable nonvertical flow. Whether or not the downflow path thus established is sustained depends upon the supply of additional heavy fluid from adjacent regions near the top of the enclosure. A second possibility is that descending chunks, stopped in any downward motion because of the opposition of the rising hot fluid, are pushed sidewise and reinforce the efforts of adjacent chunks of cooled fluid which are descending slowly. The third possibility is that descending chunks of cooled fluid are repelled by the rising stream and are driven sidewise into an already established downflow.

A downflow continues only as long as there is sufficient cool, heavy fluid to supply it. If the rate of removal of the cooled fluid exceeds its rate of production, the downflow may cease. Alternately, the downflow may move sidewise into a region (previously occupied by an upflow) in which the supply of cooled fluid (located along the top of the enclosure) is sufficient to sustain it.

The nature of the observed flow patterns did not change as the temperature difference between the heated reservoir and the cooling surface at the top of the enclosure was varied. The notable effect was a lessening of the flow velocities as the temperature difference was diminished.

There was evidence of end effects associated with both left- and right-hand end walls of the enclosure. An almost continuous downflow took place in a 3/4-inch band adjacent to both of these walls. However, at a distance of 4 inches from either end wall, the flow patterns observed were similar to those that were seen very far from these walls.

Wall-Temperature Data

Thermocouples were installed in the front and rear walls of the enclosure to detect the presence of a spatial temperature pattern which would correspond to a permanent group of upflow and downflow regions.

A representative plot of the temperature on the front wall is shown in figure 3. (The rear-wall temperatures give a similar plot.) There was little difference in the temperature at all locations. This lack of evidence of a permanent flow pattern is in accord with the visual observations. The thermal inertia of the Plexiglas wall appeared sufficient to smooth any temperature variations with time which might have arisen because of the changing flow pattern.

DISCUSSION

As has been already mentioned, the experiment reported in reference 1 on free convection in a thin annulus using liquid sodium as the working fluid gave a wall-temperature pattern from which the existence of permanent upflow and downflow regions could be inferred. These results differ from the findings of the present study. There are many differences between the two investigations the influences of which cannot be clearly evaluated. The most obvious differences are in working fluid and in geometry. An annulus, as thin as that of reference 1, might, at first, be expected to act in a fashion similar to that of a narrow rectangular enclosure of the sort used in the present study. However, the lack or presence of end walls may have some not-yet-understood effect on flow stability. The definition of the variables comprising dimensionless groups needed to insure dynamic similarity of flows of the type considered here is not at all clear.

Aside from the unevaluated factors already noted, there is a particular difference between the apparatus of the two experiments which might explain the apparent contradiction in the findings. The heat sink at the top of the enclosure in the present investigation was a smooth

copper surface. In reference 1, the cooling surface at the top of the annulus was sodium itself, which had "frozen out" during the initial stages of the operation of the system. It seems plausible to expect that the surface thus formed would not be smooth, but would have hills and valleys corresponding to the upflow-downflow pattern which developed during the initial stages of operation. Such a wavy surface, once developed, would tend to perpetuate permanent upflow-downflow patterns.

3956 A single photograph of a glass-walled annulus with water as the working fluid in which dye is used to define the streaming of the flow is included in reference 1. Sufficient information can not be obtained from this single photograph to permit comparison with results of the present investigation.

CONCLUSIONS

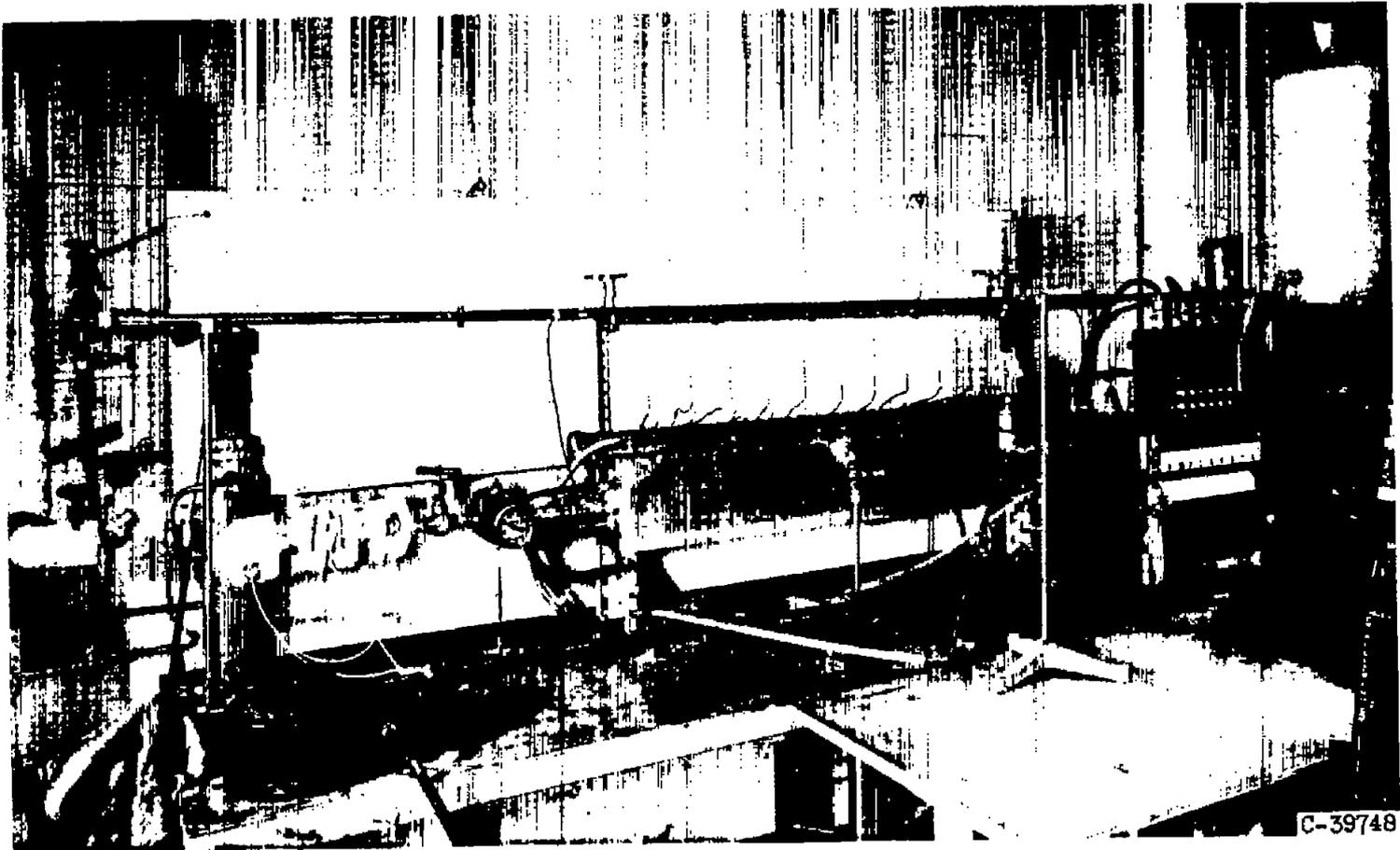
The free-convection flow of water in a narrow vertical enclosure, cooled at the top through a copper surface and open at the bottom to a heated reservoir, has been studied by means of a shadowgraph. No flow pattern was found to be steady with time, that is, no region of the enclosure is permanently a region of upflow or of downflow. Because of variations in the size of the various upflow and downflow regions arranged along the length of the enclosure at a given time and because of changes with time, neither upflow regions nor downflow regions could be characterized by a definite size. The number of upflow and downflow regions varied with time.

The dominating characteristics of the flow patterns were instability and change.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 15, 1955

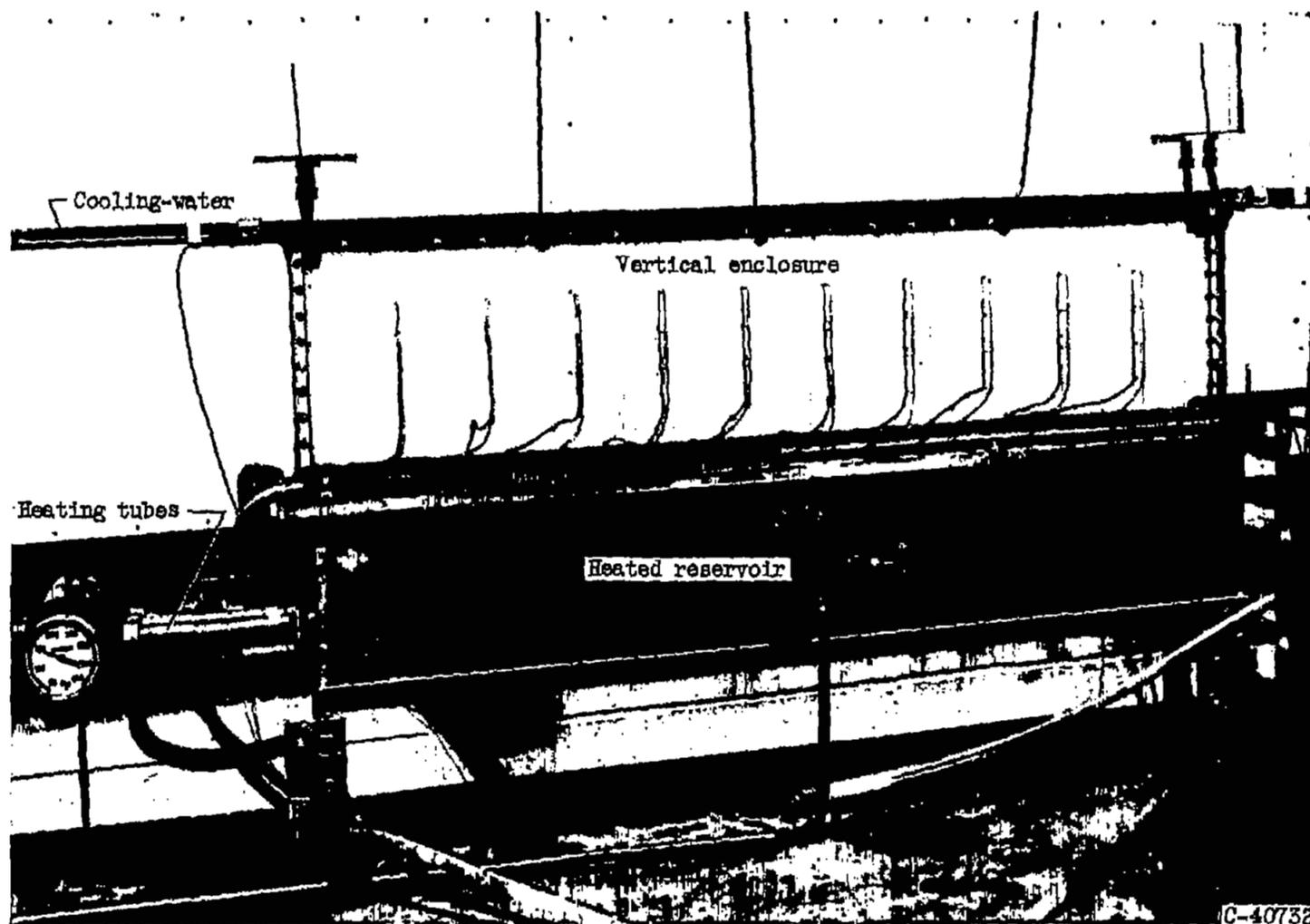
REFERENCE

1. Timo, D. P.: Free Convection in Narrow Vertical Sodium Annuli. KAPL-1082, Knolls Atomic Power Lab., General Electric Co., Mar. 5, 1954. (Contract No. W-31-109 Eng.-52.)



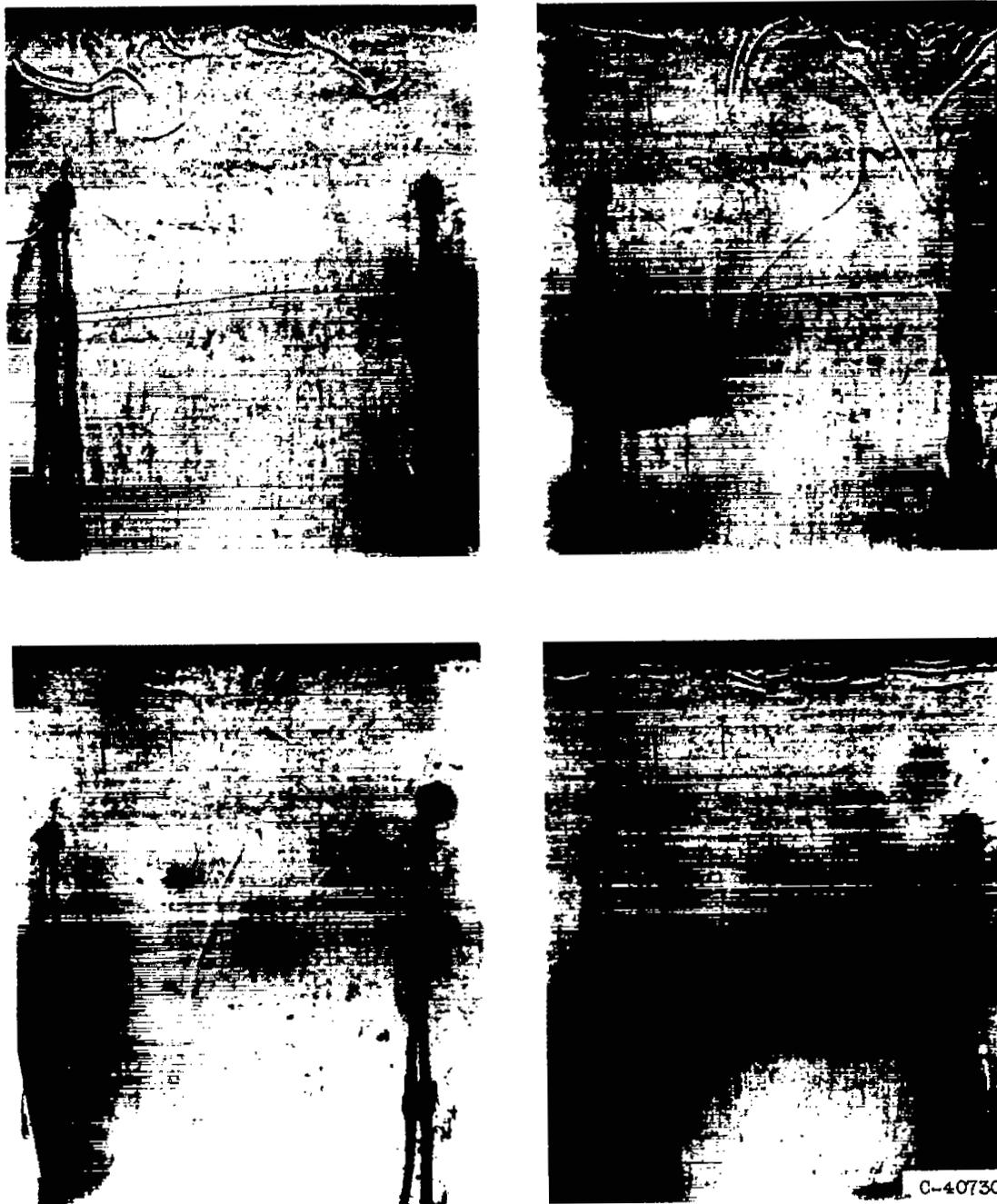
(a) Over-all view.

Figure 1. - Experimental apparatus.



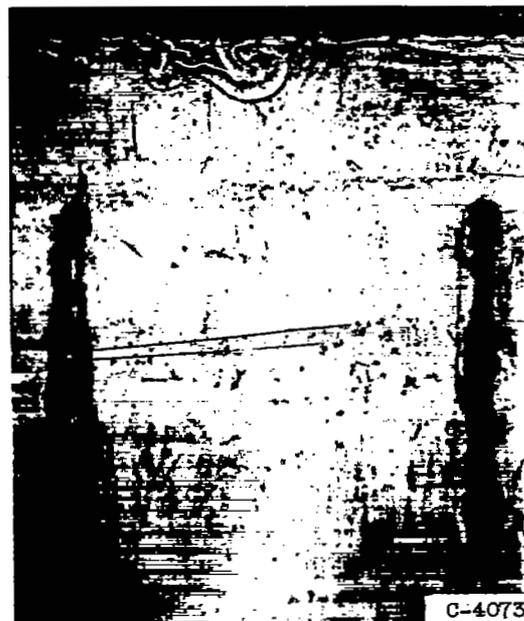
(b) Front view.

Figure 1. - Concluded. Experimental apparatus.



(a) Location, $\frac{1}{2}$ the length

Figure 2. - Representative shadowgraph photographs of flow pattern



of the enclosure.

(no time sequence is implied by arrangement of photographs).



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(b) Location, $\frac{1}{4}$ the length of the

Figure 2. - Concluded. Representative shadowgraph photographs of flow

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enclosure from the left end.

pattern (no time sequence is implied by arrangement of photographs).

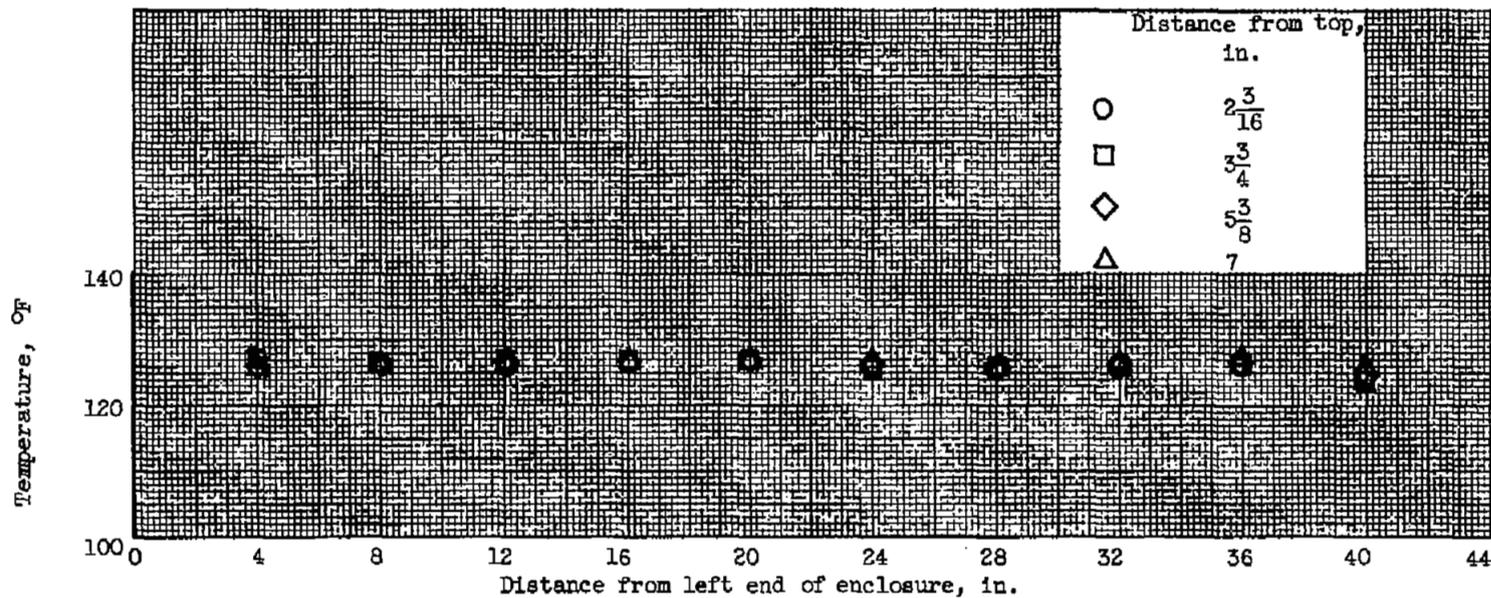


Figure 3. - Representative plot of temperature on front wall of enclosure. Distance of thermocouple tips from surface of enclosure, $1/32$ inch; temperature of reservoir, 143° F; temperature of cooling water, 72° F.

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