THE PENETRATION OF A DENSITY INTERFACE
BY HEAVY VORTEX RINGS

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Abstract. This paper describes experiments in which small volumes \( V \) of heavy fluid were released in the uppermost of two uniform layers of fluid and the degree of penetration into the lower layer determined.

When the injected fluid had no initial velocity and was initially a distance \( Z' \) above the interface between the two layers, less than about ten percent of it continued into the lower layer when \( A = (\rho_2 - \rho_1) Z'^3 / (\rho_1 - \rho_0) V \) was greater than 29; more than about 90% continued into the lower layer if \( A \) was less than 1.5. \( \rho_1 \) and \( \rho_2 \) are the densities of the upper and lower layers of fluid, respectively, and \( \rho_0 \) is the density of the injected fluid.

When the heavy fluid was injected with an initial velocity a vortex ring formed. The vortex ring was found to remain intact during its travel in the lower layer if \( A < 0.2 \left( \frac{K^2}{F} \right) \) where \( K \) is the initial circulation of the injected fluid and \( F = g (\rho - \rho_1) / \rho_1 \) \( V \) is the buoyancy parameter associated with this fluid while in the upper layer. For values of \( A < 0.3 \left( \frac{K^2}{F} \right) \), although these rings broke in the lower layer, it appeared that more than 90% of the ring fluid continued in the lower layer.

1. Introduction

The penetration of a density interface, such as an inversion in the atmosphere or a thermocline or halocline in the ocean, is important in problems of waste dispersal. For example the inversion lid structure that is observed in the Los Angeles area serves to retain pollutants which are emitted from smoke stacks within a quite shallow basin. As a result the well known smog condition develops. A similar, although upside-down, density environment is provided with a halocline in fiords for example and the thermocline in lakes and oceans. When waste is barged off-shore for dumping it is desirable to penetrate the thermocline and halocline so that the waste does not remain in the near surface waters and reduce their recreational value. This is particularly important should the dumping be done close enough to shore that waste material left in the upper layer could drift to the shore line. Turner (1960) has demonstrated that the heights to which thermals** and buoyant vortex rings will rise in an environment with a stable and linear density stratification are, much greater than corresponding heights for plumes and buoyant jets. Recently pilot-model studies† have been under taken to test the advantage of ‘smoke-ring’ generators over conventional tall smoke

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** Thermal is used to describe the convective motion arising from the instantaneous release of heavy or light fluid from a small source. The motion within a uniform fluid is then entirely prescribed by the specification of \( F \).

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stacks. This paper describes experiments that were undertaken to explore the possibility of projecting fluid through an environment that is not linearly stratified but has a relatively large change in density over a distance that is small compared with the size of a thermal.

Experimental studies of thermals penetrating the interface between uniform layers of fluid (Richards, 1961; Saunders, 1962) have related the degree of penetration to the volume of the thermal and to the densities occurring at the interface rather than to those at the point of release. The relationship between the measured penetration in terms of quantities at the interface and the source parameter $F$ was complicated because of a variability of the parameters which are required to describe the gross geometry and dynamics of the motion of a thermal. Richards suggested that these variations might be caused by an inadvertent supply of circulation in the frequently used experimental technique of inverting a hemispherical cup filled with heavy fluid (as used, for example, by Scorer, 1957; Woodward, 1959; Richards, 1961; Saunders, 1962). This interpretation gained support from the results of analogous experiments with cylindrical thermals (Richards, 1963).

In the present experiments, a different mechanism was used to release the heavy fluid, and as a result the values of the thermal parameters were roughly constant. It was found that estimated values of the degree of penetration were in agreement with values which were calculated by relating the interfacial criteria established by Richards (1961) to the initial properties of these thermals.

When initial momentum was given to the dense fluid a vortex ring was formed. The dense fluid moved faster and had a higher density on arrival at the interface than if it had moved as a thermal. The motion of the vortex ring in the uniform fluid above the interface was found to be adequately described by the equations given by Turner (1957) and which were based on similarity considerations. Such considerations do not apply when a vortex ring or thermal is near the interface where density changes abruptly.

The disruptive effects of the interface on vortex ring motion were investigated. The relations between parameters of initial circulation and density for which a ring could penetrate and remain intact, and also for which the ring fluid could continue into the lower layer, were observed experimentally.

2. Thermals

A. UNIFORM FLUID

The degree of penetration of fluid in the thermal through a density interface will depend upon the difference between a representative density of this fluid and its surroundings at the interface compared with the difference in density across the interface. However it is convenient to calculate properties of the thermal at the interface in terms of source conditions which are completely specified by $F$ for a point source.

Similarity conditions, together with the Boussinesq approximation, provide a description of the motion of a spheroidal volume $v$ of buoyant or heavy fluid within