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GAS ENTRAINMENT AT THE FREE SURFACE OF A LIQUID: ENTRAINMENT INCEPTION AT A VORTEX WITH AN UNSTABLE GAS CORE

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Experiments have been performed using sodium, water, white spirit and Freon 113 in a simple small-scale system, to determine the conditions necessary for gas entrainment inception at a vortex with an unstable gas core. The results demonstrate that surface tension effects play a major role and hence they must not be ignored when developing an entrainment-free system.

1. Introduction

In all sodium-cooled fast reactor designs there are regions where a cover gas is in contact with the sodium. If gas becomes entrained in the sodium flow this can lead to operating problems [1]. Entrainment at vortices in the liquid surface is likely to introduce large quantities of gas into the flow [2]. Since it is not possible to predict theoretically when entrainment will occur, small-scale model tests, usually with water as the working fluid, are traditionally used to develop gas-free systems. The two areas of uncertainty introduced by using such models are the consequences of using a liquid with different properties to sodium (e.g. different surface tension) and the influence of change of scale.

Earlier studies have considered entrainment at a vortex with a stable gas core, that is, a vortex where the flow towards the centre of rotation is laminar [3]. This work is an investigation of the parameters which control the behaviour of a vortex where the gas core is unstable.

2. Experimental work

Experiments have been performed to detect the onset of entrainment at unstable vortices in sodium, water, white spirit and Freon 113*. The geometry used for all fluids is shown in fig. 1. The vortex results from the circulation generated by introducing the flow into the vessel tangentially. The liquid exits via the outlet pipe in the centre of the vessel base.

The tests with water, white spirit and Freon 113 were performed in a glass aparatus. Since all three liquids are transparent this made it possible to observe the air core in the vortex with the naked eye. The gas core

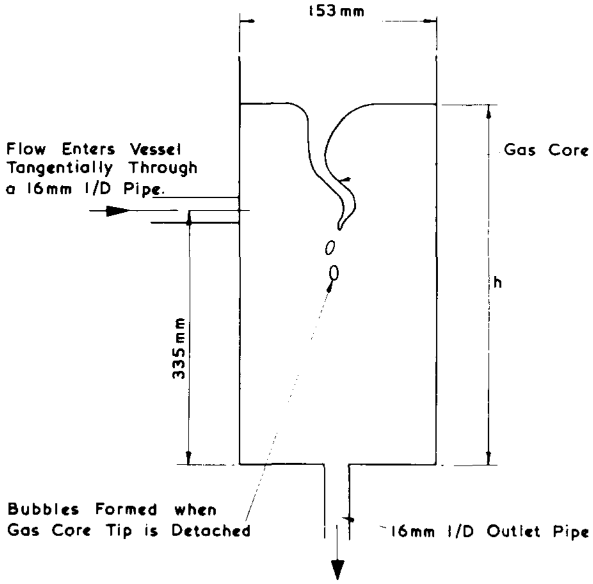

Fig. 1. Geometry used in the experiments.

* Dupont trade name for $F_2ClC-CFCl_2$.

could be seen to display the usual characteristics of a gas core in an unstable vortex, i.e. at a given flow rate it meandered and continuously varied in length.

In addition, the gas core tip would occasionally break away, forming a few bubbles. In a non-entraining situation these bubbles subsequently rise under the action of buoyancy force and reattach to the gas core.

This behaviour was only present when the flow in the inlet pipe was turbulent. With laminar flow in the inlet pipe the gas core was similar to that observed in the laminar vortex studies [3] where at a given flow rate the gas core was stationary, of fixed length and symmetrical about the axis of the outlet.

Entrainment inception at an unstable vortex occurs when the flow rate is such that the gas core tip approaches sufficiently close to the outlet that the bubbles formed by the break away at the gas core tip are swept into the outlet. The diameter of the bubbles entrained in the tests with water, white spirit and Freon were of the order of 2 mm dia.

In the tests with liquids other than sodium the onset of entrainment was taken to be the condition when gas was first observed to enter the outlet pipe. Further increases in flow beyond the inception value caused the gas core to become continuous into the outlet with consequent increase in the rate of gas entrainment.

For the sodium tests the apparatus was constructed of stainless steel and mounted in the Number One sodium loop at Berkeley Nuclear Laboratories [4]. The onset of entrainment was detected using an electromagnetic bubble detector [5] mounted on the outlet pipe. This bubble detector consists of an a.c. drive coil on one side of the pipe, and diametrically opposite two detection coils separated axially along the pipe; the detection coils are connected to give a balanced signal when no bubbles are present. The minimum size of bubble detectable by this method (i.e. which produces a detectable imbalance in the system as it passes the coils) is 0.5 mm dia.

The experimental procedure followed in all cases was to fill the system to a depth h and then increase the flow rate in small steps, thus increasing the gas core length, until entrainment occurred. In the sodium tests the liquid level could only be varied over a limited

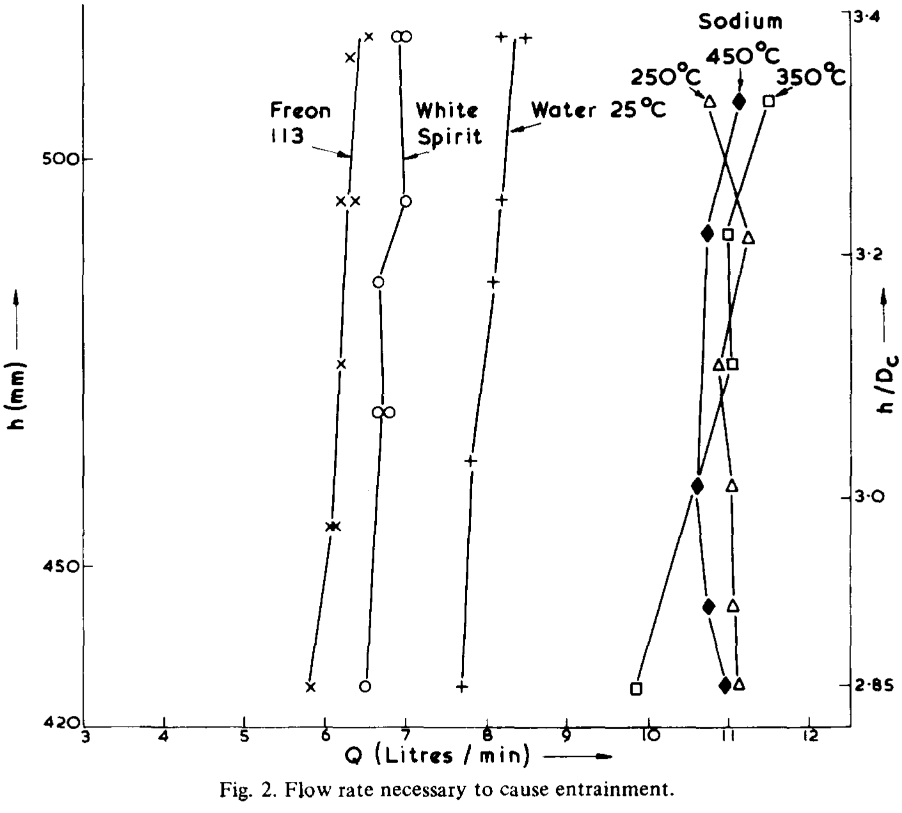

Fig. 2. Flow rate necessary to cause entrainment.

range (i.e. h = 435–510 mm) because of problems with seals on the vessel, but this range was sufficient to provide a comparison with the other fluids. The results over this range are shown in fig. 2 (D_c is the diameter of the vessel). The sodium flow rates are accurate to within ±3% and the flow rates of the other liquids to within ±1%.

3. Discussion

Patterson and Campbell [6] state that, besides inertia, the forces which could be involved in vortex forming situations, e.g. pump sumps, are gravitational, viscous and surface tension forces. Thus, it may be assumed that for a given liquid depth h entrainment inception is a function of the characteristic velocity of the system V, a characteristic system dimension L, liquid viscosity μ, liquid density ρ, surface tension T, and gravitational acceleration g. Consequently, applying Buckingham's π theorem [7] gives an expression for the condition for entrainment inception of the form

$$h/L = f(Re, Fr, We),$$

where Re is the system Reynolds number $VL/(\mu/\rho)$; Fr is the system Froude number V^2/gL; and We is the system Weber number $V^2L/(T/\rho)$.

In the present work the vessel diameter D_c is taken to be a characteristic dimension. The properties of the liquid appear in Re and We and thus, in order to determine the influence of the liquid properties on entrainment inception, the experimental results were replotted as Q, the flow rate necessary to produce entrainment inception, against μ/ρ and Q against T/ρ for various values of h (see figs 3 and 4).

Figure 3 implies that if μ/ρ, and hence Reynolds number, alone, is the dominant influence on entrainment inception, then for a liquid with $\mu/\rho < 1.2$ centistokes there would be two flow rates at which entrainment inception would occur, which is physically impossible. However, since in fig. 3, h, L and g are fixed, the large difference between the inception flow rates for Freon 113 and sodium at 250°C, which have the same value of μ/ρ, can only be attributed to T/ρ. In addition, Q displays a linear variation with T/ρ in fig. 4. Thus entrainment inception can be expected to include a strong dependence on Weber number.

In fig. 5 the results are plotted as h against $\rho Q^2/T$, which is proportional to the Weber number for the system. If Weber number alone determined the onset of entrainment then all the results should lie on the same line. In fact the ratios of $\rho Q^2/T$ for sodium at 450°C to $\rho Q^2/T$ for the other liquids, denoted by A, are shown in table 1.

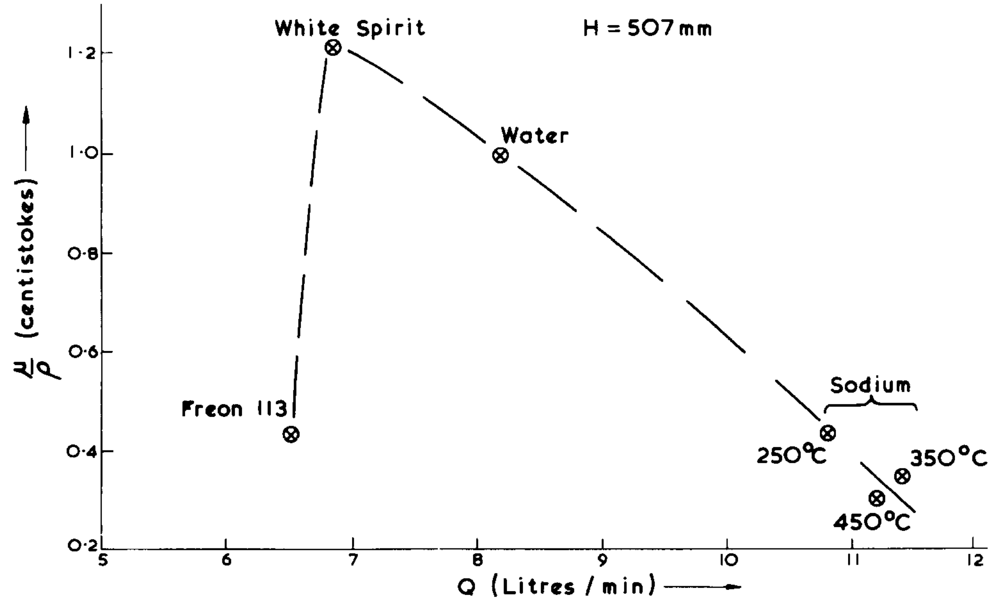

Fig. 3. The influence of μ/ρ on Q.

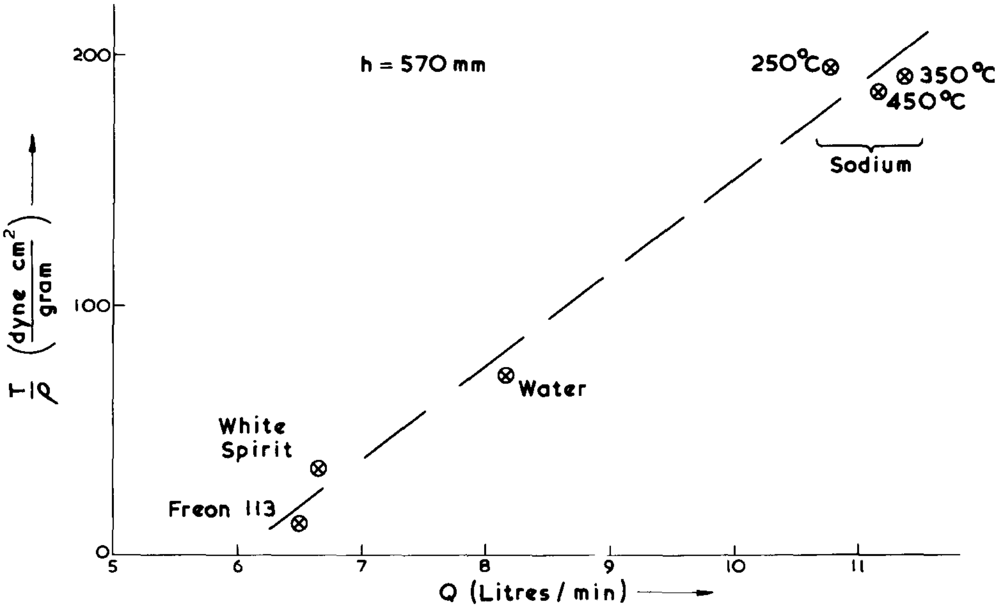

Fig. 4. The influence of T/ρ on Q.

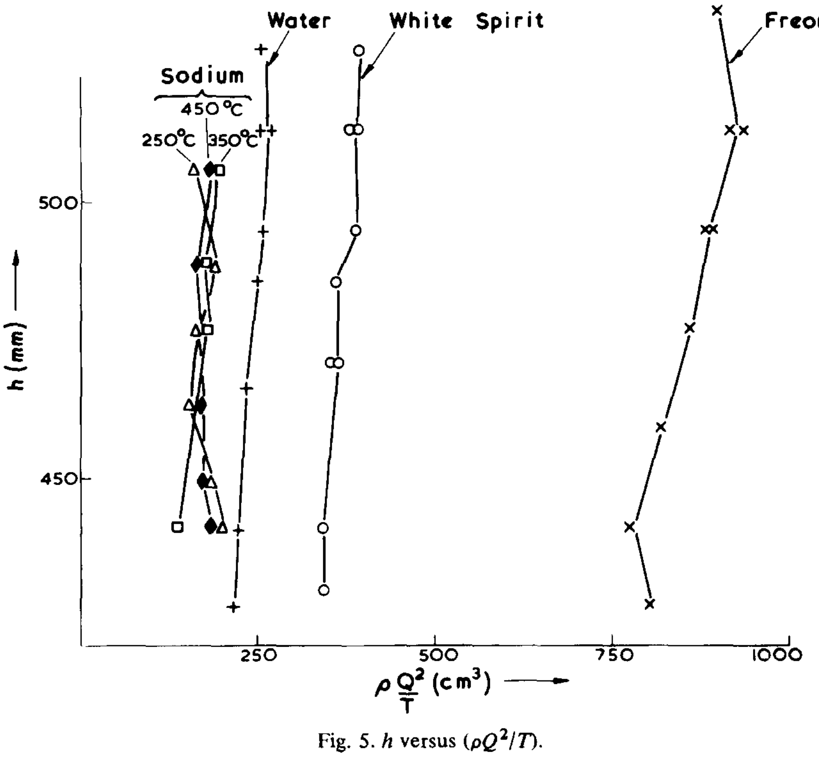

Fig. 5. h versus $(\rho Q^2/T)$.

Table 1.
Comparison of experimental and predicted values for A.

	$\dfrac{\left(\frac{\rho Q^2}{T}\right)_{\text{sodium }450^\circ\text{C}}}{\left(\frac{\rho Q^2}{T}\right)} = A$	$\left\{\frac{\rho}{T}\Big/\left(\frac{\rho}{T}\right)_{\text{sodium }450^\circ\text{C}}\right\}^{0.5}$,	$\dfrac{\left(\frac{\rho}{\mu}\right)_{\text{sodium }450^\circ\text{C}} \times Q}{\left(\frac{\rho}{\mu}\right) \times Q_{\text{sodium }450^\circ\text{C}}}$
Freon 113	0.20 → 0.24	0.25	1.18 → 1.32
White spirit	0.44 → 0.5	0.43	0.39 → 0.42
Water (25°C)	0.66 → 0.73	0.625	0.39 → 0.42
Sodium (350°C)	≈1	1.016	0.68 → 0.76
Sodium (250°C)	≈1	1.035	0.82 → 0.85

It is not possible with water, white spirit or Freon 113 to simultaneously obtain the same relative magnitudes of inertia, gravitational, viscous and surface tension forces as in sodium, i.e. the sodium *Re*, *Fr* and *We* cannot be achieved simultaneously. Thus, assuming the mechanism of entrainment is the same for both sodium and the other liquids, entrainment inception at a given h/D must be primarily a function of *Fr* and *We* or *Re* and *We*. Now for two systems, B and C, in which the Weber and Froude numbers are matched the following conditions are satisfied:

$$(\rho V^2 L/T)_B = (\rho V^2 L/T)_C \tag{1}$$

and

$$(V^2/gL)_B = (V^2/gL)_C. \tag{2}$$

Eliminating the effects of scale between (1) and (2) gives

$$\left(\frac{\rho V^2}{T}\right)_B \Bigg/ \left(\frac{\rho V^2}{T}\right)_C = \left\{\left(\frac{\rho}{T}\right)_C \Bigg/ \left(\frac{\rho}{T}\right)_B\right\}^{0.5}. \tag{3}$$

Since for a single scale system $V \propto Q$, the condition necessary for entrainment inception to be a function of Froude number and Weber number is that A should have the value

$$\left\{\left(\frac{\rho}{T}\right) \Bigg/ \left(\frac{\rho}{T}\right)_{\text{sodium }450^\circ\text{C}}\right\}^{0.5}.$$

Similarly if matched *Re* and *We* are necessary for entrainment inception then A would have the value

$$\left\{\left(\frac{\rho}{\mu}\right)_{\text{sodium }450^\circ\text{C}} \times Q\right\} \Bigg/ \left\{\left(\frac{\rho}{\mu}\right) \times Q_{\text{sodium }450^\circ\text{C}}\right\}.$$

It is evident from table 1 that, while there is little similarity between A and the group necessary for matched *Re* and *We*, A and the group necessary for matched *Fr* and *We* are almost identical. Hence it is concluded that for a given h/D_c the onset of entrainment is primarily a function of Weber number and Froude number.

The Weber–Froude criterion implies that the scale required for models that are used with liquids other than sodium to simulate the entrainment inception in sodium is

$$\{(\rho/T)_{\text{sodium}}/(\rho/T)_{\text{other liquid}}\}^{0.5},$$

(obtained by eliminating V between eqs (1) and (2)), and that entrainment inception occurs when liquid velocity = $(\text{scale})^{0.5}$ x (sodium velocity necessary for entrainment inception in full scale component); e.g. using water at 25°C to simulate sodium at 450°C the scale required is 0.625 and entrainment inception should occur when the water flow is 30% of the sodium flow rate necessary for entrainment inception in the full scale component.

Thus a further experiment to confirm the Weber–Froude criterion was performed with water in a 0.625 scale model of the original system. Over the range of h/D_c where sodium results are available (i.e. h/D_c = 2.8 → 3.4) entrainment inception occurred at flow rates between 31 and 35% of the 450°C sodium inception flow rates. Hence, the similarity of these percentages to the predicted 30% reinforces the view that entrainment inception at a turbulent vortex is primarily a function of *We* and *Fr*.

By comparing the water results at the two scales the relationship between h, D and V

$$\left\{V = \frac{Q}{(\pi/4)D_c^2}\right\}$$

at entrainment inception was determined. This together with the linear relationship between T/ρ and V at given h and scale leads to a general correlation for all the results in the present series of tests, i.e. for a range of h/D_c of 2.2 to 4.0 the critical condition for entrainment inception is

$$h/D_c = 700\,(Fr^{0.5} - 4.4\,Fr/We). \qquad (4)$$

This relationship is shown in fig. 6.

In this experiment the perimeter of the rotating liquid lay on a diameter of 153 mm. Now for sodium, if, keeping h/D_c fixed, D_c is increased to say 600 mm, then the effect on the terms in eq. (4) is that $4.4(Fr/We) \ll Fr^{0.5}$, i.e. the surface tension effects become negligible. Thus eq. (4) only applies to vortices generated in small confined spaces, and the scale of the model which will give the correct simulation of entrainment inception in this situation is determined by the need to model both We and Fr, and hence depends on the liquid employed. If water is used to simulate sodium a $\frac{5}{8}$ scale model is necessary.

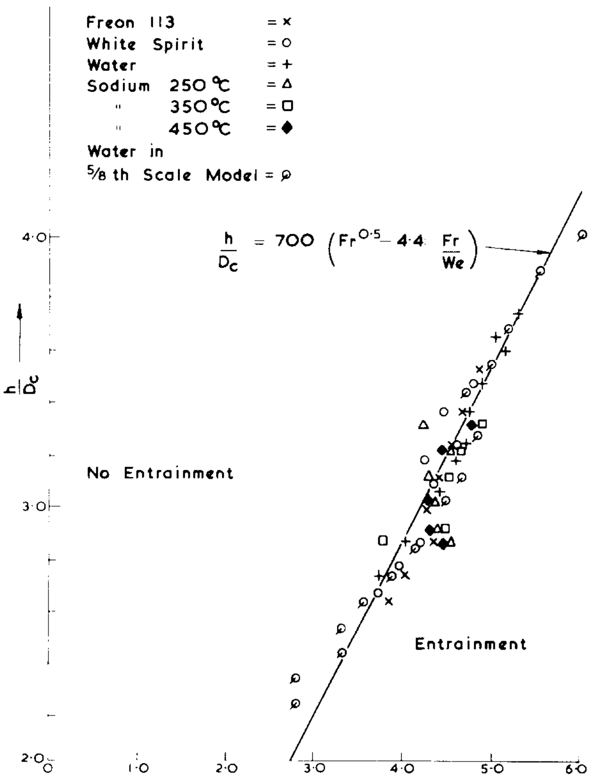

Fig. 6. Correlation of all results.

The results in fig. 2 show that at a flow rate of 9 l/min gas was entrained for water flow but not for sodium flow. This implies that in water tests in full-scale components prior to sodium commissioning, entrainment at small-scale vortices is more likely at the design flow in the water tests than for sodium flow. Thus if entrainment at small-scale vortices can be eliminated in the water tests in the full-scale component, it is most unlikely that there will be entrainment in sodium.

It must be emphasized that eq. (4) is specific to the present geometry, and the entrainment inception criteria for other geometries can only be obtained by experiment, e.g. there may be geometries where Reynolds number effects play a significant role. However, the present work does demonstrate that surface tension effects must not be ignored where there is the possibility of unstable vortices being generated in confined spaces.

Also, in contrast to the earlier work on entrainment at a laminar vortex [3], surface tension effects are significant at large values of h/d, where d is the diameter of the outlet pipe (d/D_c in the present system was of the same order as in the laminar vortex work, i.e. ≈ 0.1).

4. Conclusions

Experiments in a simple small-scale system have been performed to determine the onset of gas entrainment at a vortex with an unstable gas core. Four liquids were used (sodium, white spirit, water and Freon 113) and the general correlation of the results is

$$h/D_c = 700\,(Fr^{0.5} - 4.4\,(Fr/We).$$

The above correlation is specific to the geometry used in the experiment but it does demonstrate that surface tension effects must not be ignored when attempting to eliminate entrainment in any situation where small-scale unstable vortices are present.

Acknowledgement

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Nomenclature

A = $\{(\rho Q^2/T)_{\text{sodium } 450°\text{C}}\}/(\rho Q^2/T)$
d = diameter of the outlet pipe
D_c = vessel diameter = diameter of volume of rotating liquid
h = liquid depth
L = characteristic dimension of the system
Q = flow rate necessary to cause entrainment inception
T = surface tension
V = characteristic velocity of the system
ρ = density
μ = viscosity
Re = Reynolds number = $\rho VL/\mu$
Fr = Froude number = V^2/gL
We = Weber number = $\rho V^2 L/T$.

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