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Cavities formed on liquid surfaces by impinging gaseous jets

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Experimental tests of an axisymmetric jet of air impinging on both water and wet cement were performed and analyzed. Since the cavities formed on the water were unsteady and irregular, cavities were formed on wet fast-setting cement and allowed to set with the jet impinging. In this way, detailed measurements of the solidified cavity shape were made and shown to agree well with theory. This correlation of the data with the theory indicates that little gas was entrained in the liquid and that the influence of liquid viscosity and surface tension was small for the experimental conditions tested. A simplified analysis is also presented for an incompressible axisymmetric gas jet impinging normally on a liquid surface. The analysis was effected by combining the following physical conditions and assumptions: (i) the stagnation pressure corresponding to the centreline conditions of the jet at the bottom of the cavity is equal to the hydrostatic pressure, wherein an empirical turbulent jet decay law is used to predict the variation of stagnation pressure with distance from the nozzle; (ii) the force on the liquid is equal to the total change in normal momentum, which is equal to the weight of the displaced liquid; (iii) the shape of the cavity is a paraboloid.

1. Introduction

This paper describes an experimental investigation of the phenomena associated with the impingement of a gaseous jet on a liquid surface. This general type of problem is encountered in a number of fields. The phenomenon is met when a ground effect machine operates over water or over a terrain which is easily deformed, such as mud or sand. Vertical-take-off-and-landing craft also experience a similar problem where erosion of the landing surface can result in loss of visibility and also cause damage to the craft by recirculating debris. In the steel industry, the basic oxygen conversion process, which was the motivation for this study, utilizes a supersonic jet of oxygen impinging on molten iron to convert the iron to steel.

The problem of jet impingement on liquid surfaces has been studied by a number of investigators. Olmstead & Raynor (1964) considered the limiting two-dimensional case of slight depressions in the liquid surface and were able to find analytical predictions of the surface shape by use of conformal mappings. An

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exact analytical solution of the large depression cavity may never be achieved because of the difficulty of the interaction of the shape of the surface and jet flow. Collins & Lubanska (1956) experimentally studied circular air jets of varying momentum impinging on water at various angles. Mathieu (1960) and Maatsch (1962) also performed experiments on air jets impinging on water. Glass & Hays (1963) report on experimental results obtained by jetting air on various liquids and oxygen on molten iron. Banks & Chandrasekhara (1963) presented a detailed experimental and theoretical study of axisymmetric and two-dimensional air jets impinging on water. The theoretical technique used in the present study is similar to their approach with differences in the analysis as well as in the experimental techniques. It is perhaps worth noting that cavities formed in solid surfaces by impacting meteorites or high-velocity profiles are very similar to the cavities observed in this study.

This paper is concerned with the experimental determination of cavity depth and diameter when an incompressible gas jet impinges normally on a liquid surface and with the comparison of these experimental results with theoretical predictions. In this paper, the experimental results are first presented and then comparison is made with the theoretical results. Air was used in all experiments and blowing height and nozzle driving pressure were varied. Water and fast-setting cement were used as the liquids. The use of cement allowed a permanent record of the cavity to be obtained as well as accurate measurements of the shape.

2. Experimental investigation

The aim of the experiments was to determine cavity geometry for a range of blowing conditions. Cavity profiles were photographed in a 12 in. diameter and 24 in. high Pyrex jar filled with water to a depth of 7 in. Optical distortion of the circular cylinder was eliminated by placing it in a square cylinder also filled with water. Laboratory air at 110 psig (pounds per square inch gauge), throttled to the desired pressure, was passed through a $\frac{1}{4}$ in. pipe and into a converging nozzle with an upstream diameter of 0·343 in. and throat diameter of 0·055 in. These experiments were conducted with a sonic nozzle attached to a pipe mounted so that it could be moved in a vertical direction. An accurate measurement of the height of the nozzle above the liquid surface was made by means of a pointer attached to the pipe referencing afixed scale.

To obtain a record of the cavity shape for each run, a photograph was taken of the cavity in the water surface caused by the impinging jet of air. The depth and diameter of the cavity were measured from the photograph.

Owing to oscillation of the cavity, it was difficult to define an exact boundary and a solidified boundary shape was desired. This was achieved by use of a cement ('Floorstone' brand) which resembles the cement used in concrete. A large proportion of water was used so that the water–cement mixture had a viscosity slightly higher than that of water and an average specific gravity of 1·62. A typical run consisted of first setting the desired mass flow of air and height of nozzle. The mixture of cement and water was mixed and weighed for a specific gravity measurement and then placed under the air jet and allowed to harden. The cavity obtained was always of the same shape throughout the blowing except, of course, for the surface waves which formed. The cavity oscillations did not affect the final result. After setting, detailed measurements were made of the shapes.

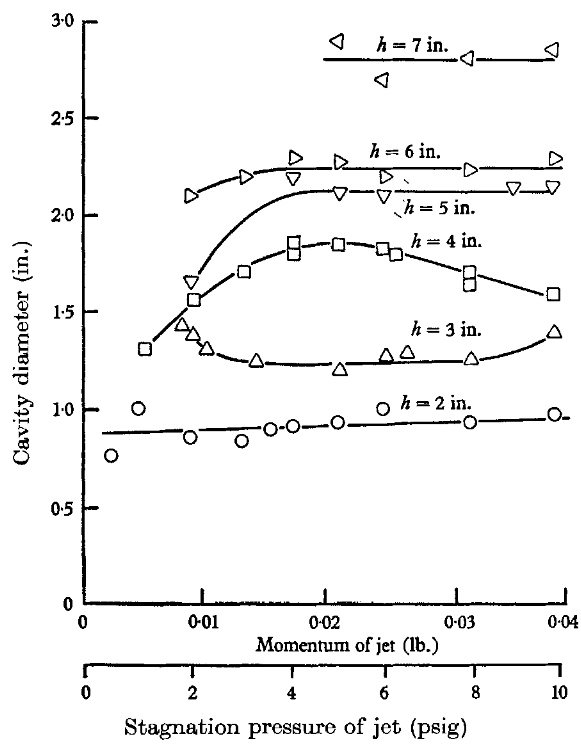

FIGURE 4. Variation of cavity diameter with height of nozzle and momentum of jet.

Photographs of the cavities formed by a mild jet condition and a somewhat stronger jet are shown in figures 1 and 2, plate 1. All of the cavities exhibited a smooth bottom and measurements of the cavity profile were in good agreement with the assumed parabolic shape. Figure 2 shows the formation of protuberances which could be sprayed off in a lower-viscosity water cavity. These disturbances, typical of some cavities, represent an instantaneously hardened cavity.

Figure 3, plate 2, is a photographic summary of the cement cavity tests. If the lower left-hand corner of this array is considered as an origin, then the array is arranged as a photographic plot showing the variation of nozzle stagnation pressure (psig) along the abscissa and nozzle height (inches) above the liquid along the ordinate. Several trends can be seen on this photographic plot: for an increase in stagnation pressure at a given height, the cavity diameter is approximately constant; for increases in nozzle height, the cavity diameter increases approximately linearly. Further, as nozzle pressure increases and height decreases, the penetration increases. The deepest cavity appears at the lower right-hand corner of figure 3 (the bottoms of the cement models in this region are more difficult to see because of the low angle of the photoflood lamp which illuminated the cavities for the picture). If an imaginary line is drawn from the lower left-hand corner to the upper right-hand corner of the picture (approximately along the diagonal), then above this line smooth cavities exist and, below, the cavities show the presence of waves or liquid shedding.

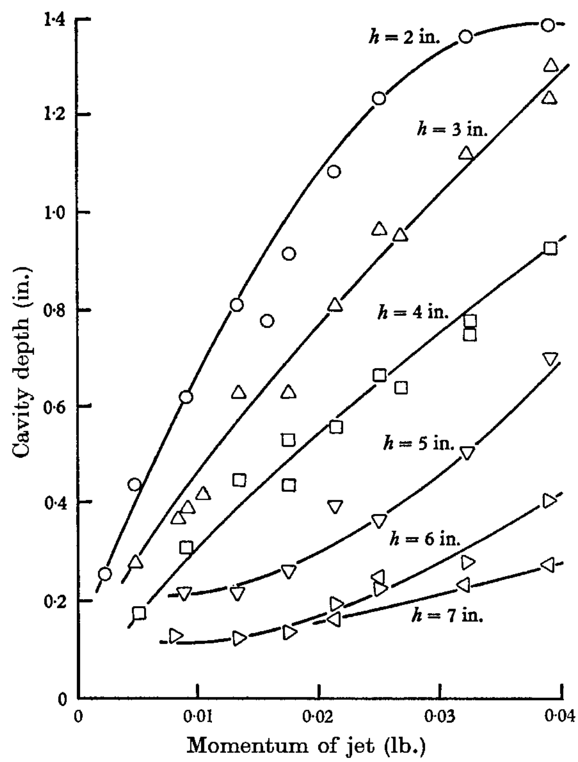

FIGURE 5. Variation of cavity depth with height of nozzle and momentum of jet.

The measured cavity diameters and depths for the air–cement series are shown in figures 4 and 5 respectively. The relative insensitivity of cavity diameter to jet momentum can be noted (although there appears to be a transition behaviour around $h = 4$ in.).

3. Theoretical predictions

In the analysis the cross-sectional shape of indentation is assumed to be a parabola of depth a (in.) and diameter d_c (in.), so that the cavity is a paraboloid for axisymmetric flow. This assumption is chosen because of the known close resemblance to the actual shape and of the great simplification it allows in the analysis. The reflected jet is assumed to leave the cavity at an angle θ, the angle of the parabola at the liquid surface (as shown in figure 6), without a change in the magnitude of the jet velocity. Thus viscous shear between the jet and liquid is neglected. It is also assumed that the total pressure force on the cavity is equal to the weight of the displaced fluid. Applying the momentum theorem to a control volume (figure 6) around the cavity and simplifying:

$$\zeta_3 = 2^{\frac{3}{2}}[M_3/\pi - 1 + (2M_3/\pi + 1)^{\frac{1}{2}}]^{\frac{1}{2}}, \tag{1}$$

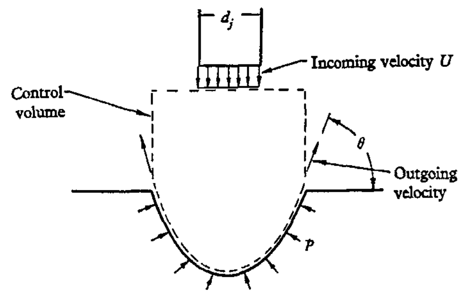

FIGURE 6. Assumed paraboloid shape.

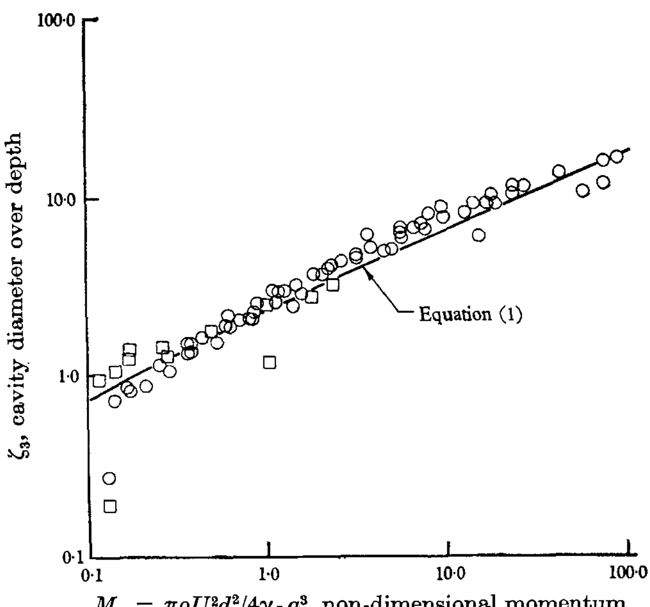

FIGURE 7. Plot of ζ_3 versus M_3 (experimental air–water tests) and equation (1). ○, experimental results of Banks & Chandrasekhara (1963); □, experimental results of this investigation.

where M_3 is a non-dimensional axisymmetric momentum $M/\gamma_L a^3$, M is the momentum (lb.), γ_L is the specific weight of liquid (lb./ft.^{3}) and ζ_3 is a non-dimensional cavity diameter d_c/a. The subscript 3 denotes three-dimensional studies. For a more complete theoretical solution see Banks & Chandrasekhara (1963).

Inspection of (1) shows that for small M_3, i.e. $M_3 \ll \pi$,

$$\lim_{M_3\to 0} \zeta_3 = (16M_3/\pi)^{\frac{1}{4}}. \tag{2}$$

M_3 small indicates that ζ_3 is also small or that a narrow cavity exists. This corresponds to the case of hard blowing or deep penetration.

Although jet velocity was assumed uniform it is readily shown that (1) remains valid even when the jet velocity is variable and when the jet decays owing to turbulent mixing, as long as M is taken as the total jet momentum. Equation (1) is plotted in figure 7 along with the experimental data of Banks & Chandrasekhara (1963) and the results of this investigation. Comparisons will be made later. Equation (1) contains two unknowns, cavity diameter and penetration. The additional equation needed to completely solve the problem is presented in the following section along with the blowing height, which is a parameter of the problem.

4. Depth correlation models using turbulent jet theory

If we neglect surface tension and shear on the cavity wall, the gas penetration depth into the liquid is determined by the dynamic pressure associated with the centreline velocity of a free, turbulent, incompressible jet. Because of viscous mixing, the centreline velocity decays with distance from the nozzle. The centreline velocity at the undisturbed surface level of the liquid can be obtained from

$$V_c/V_j = K_2 d_j/h \tag{3}$$

where K_2 is an empirically determined constant. The subscripts c and j refer to the cavity and jet respectively. Thus V_j is the velocity of the jet (ft./sec) and V_c is the centreline velocity of the jet (ft./sec). The value $K_2 = 6{\cdot}4$ is an average value as determined from Albertson, Dai, Jensen & Rouse (1950), Corrsin & Uberoi (1949), Faris (1963), Folsom & Ferguson (1949) and Hinze & Van der Hegge Zijnen (1948) for axisymmetric jets. Inserting (3) into the Bernoulli equation,

$$\gamma_L a = \tfrac{1}{2}\rho V_c^2,$$

where ρ is the density of the jet (slugs/ft.^{3}) and solving for a/h in terms of the momentum of the jet, where h is the height of the nozzle above the liquid (in.):

$$a/h = (2K_2^2/\pi)\,(M/\gamma_L h^3). \tag{4}$$

As a refinement for deep cavities, h is replaced by $h+a$ in (4) (as done by Banks & Chandrasekhara (1963)) so that

$$M/\gamma_L h^3 = (\pi/2K_2^2)\,(a/h)\,(1+a/h)^2. \tag{5}$$

This relation is similar to that of Banks & Chandrasekhara (1963); it differs in the form of the non-dimensional momentum. Equation (4) is noted to be the asymptote of (6) for small values of $M/\gamma_L h^3$. For large $M/\gamma_L h^3$,

$$a/h = [(2K_2^2/\pi)\,(M/\gamma_L h^3)]^{\frac{1}{3}}. \tag{6}$$

Equations (4), (5) and (6) are plotted in figures 8 and 9.

In addition to the cavity depth, the cavity diameter at the surface of the liquid is also of interest. Rewriting (1):

$$d_c/h = (8)^{\frac{1}{2}}\,(a/h)\,\{(M/\gamma_L h^3)\,(1/\pi)\,(h/a)^3 - 1 + [(M/\gamma_L h^3)\,(2/\pi)\,(h/a)^3 + 1]^{\frac{1}{2}}\}^{\frac{1}{2}}, \tag{7}$$

where a/h is determined from (5).

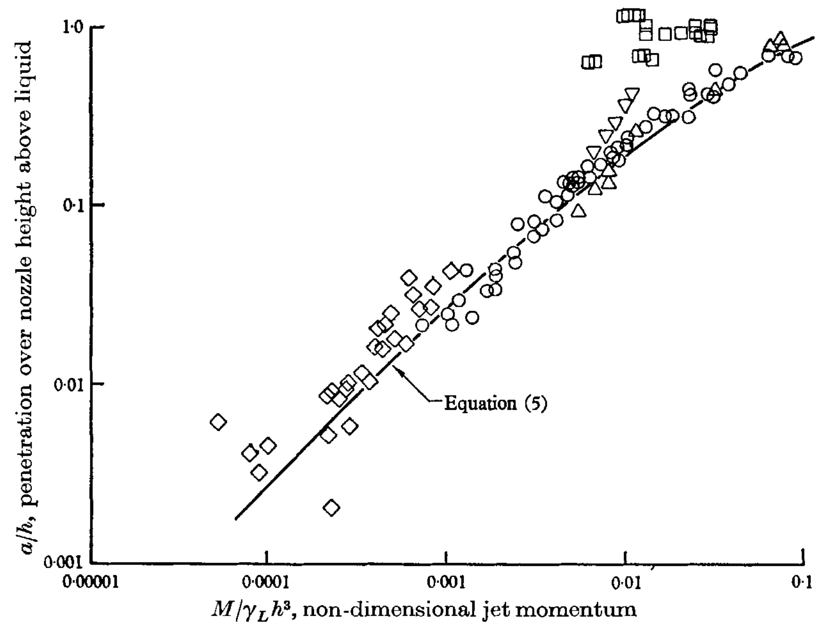

FIGURE 8. Plot of a/h versus $M/\gamma_L h^3$ (experimental) and equation (5). ◇, Banks & Chandrasekhara (1963); ▽, mercury; ○, cement; △, water; □, molten iron (oxygen jet).

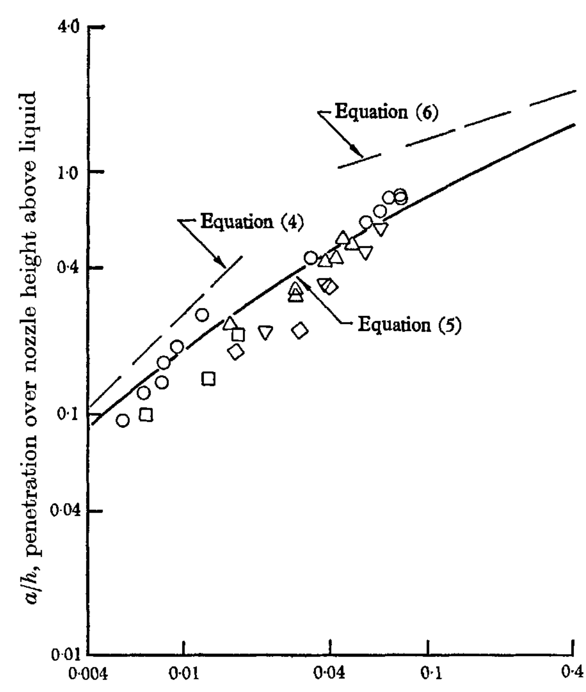

FIGURE 9. Plot of a/h versus $M/\gamma_L h^3$ (experimental) and equations (4), (5) and (6). □, acetylene tetrabromide; ◇, glycerine; △, trichloro-ethane; ○, water.

5. Comparison of theoretical and experimental results

The penetration results, along with those for the air–water tests, are plotted in non-dimensional form in figures 7, 8 and 9. The molten iron (oxygen jet), mercury, acetylene tetrabromide, glycerine, trichloro-ethane (air jet) results of figures 8 and 9 are those of Glass & Hays. Theoretical predictions as well as experimental data from Banks & Chandrasekhara (1963) are also included on these figures.

In general, agreement between experiment and theory is good. The cement cavities show best agreement due to the accuracy of measurements. The shallow-water experiments of Banks & Chandrasekhara (1963) ($a/h < 0{\cdot}01$) show a general disagreement; however, this is understandable since these measurements were in depths of the order of 0·01–0·1 in. and in this range the oscillating cavity precludes accurate measurements. The penetrations for the case of oxygen impinging on molten iron (figure 8) are much larger than for the air/inert liquid case. Chemical reactions involved in the oxygen/molten iron combination account for this discrepancy.

6. Conclusions

From the results obtained in this study, the following conclusions are made regarding the impingement of gas jets on liquids: (i) the change in the vertical momentum of a jet impinging on a liquid surface is equal to the weight of displaced fluid; (ii) the depth and diameter of the axisymmetric cavities induced by jet impingement can be predicted by simple relations; (iii) a paraboloid is a good approximation to the cavity shape; (iv) there exists a jet velocity over the surface of the cavity above which spraying or sputtering will occur and below which a smooth cavity exists; (v) liquid and gas viscosity and liquid surface tension do not affect the results.

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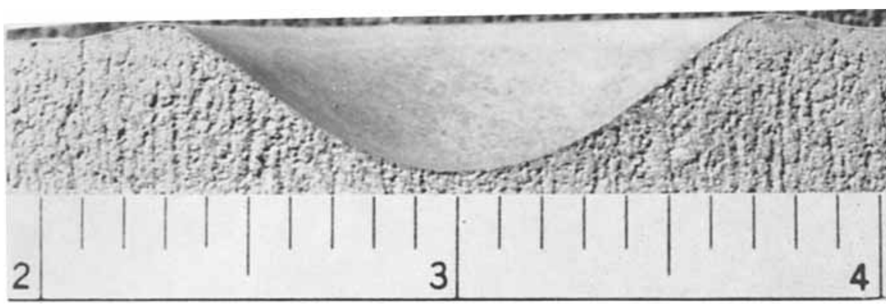

FIGURE 1. Cavity formed by air jet impinging on wet cement.
(M = 0·0090 lb., h = 3 in.)

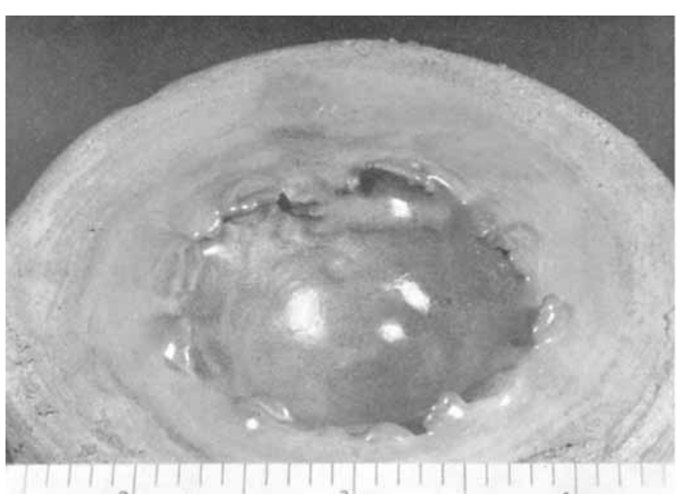

FIGURE 2. Cavity formed by air jet impinging on wet cement.
(M = 0·0323 lb., h = 4 in.)

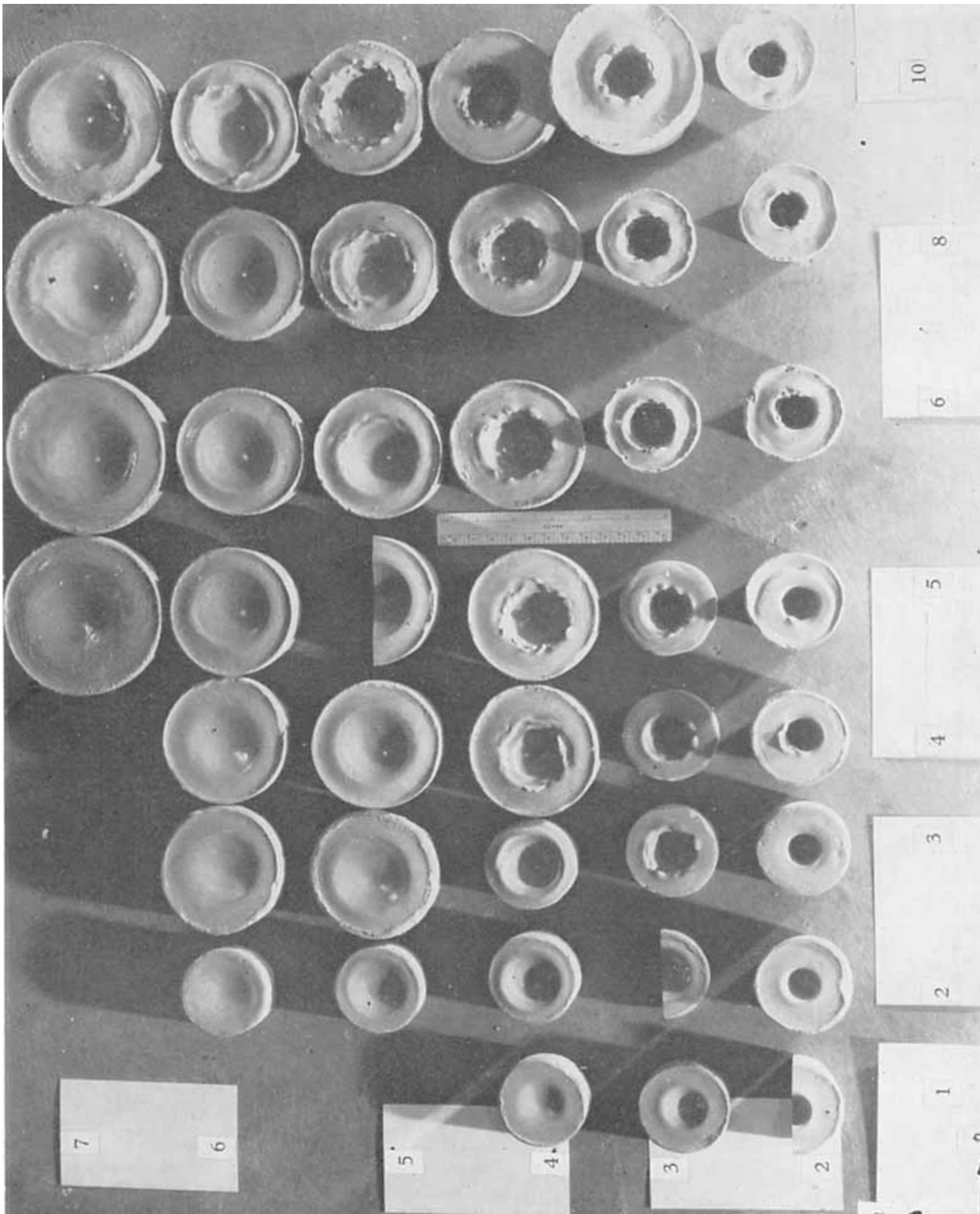

FIGURE 3. Photographic plot of cement cavities; height of nozzle, h, along ordinate (in.), stagnation pressure of nozzle along abscissa (psig).