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RESEARCH ON THE
ANNULAR LITHIUM JET CONCEPT
FOR FUTURE LASER-FUSION REACTORS

September, 1977 to December, 1978

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ANNULAR LIQUID JET EXPERIMENTS

Myron A. Hoffman and Ronald K. Takahashi

ABSTRACT

Experiments have been performed to determine the length for convergence or closure of a vertical, hollow annular water jet due to the action of surface tension forces. The data agree well with theoretical predictions up to a velocity of about 3 m/s. At higher velocities, the convergence lengths are less than predicted and this is attributed to the jet acting as an ejector pump and thereby reducing the air pressure inside the annulus to slightly sub-atmospheric values. The stability of such a jet is also discussed in the light of the fact that no hydrodynamic instabilities have been observed to date. Finally the results of a series of experiments on the flow spreading or splitting due to the presence of wedge-shaped obstacles in the path of the annular jet flow are described.

SYMBOLS

- $\bar{a}$ = mean annular nozzle radius
- b = annular jet thickness
- $Fr = V_0^2/g \bar{r}_0$ = Froude number
- g = acceleration of gravity
- L^* = convergence or closure length
- $N_c = \rho g^2 \bar{r}_0^2 b_0 / 2V_0^2 \sigma$ = convergence number
- r = radial coordinate
- $\bar{r}$ = mean radius of the annular jet
- $\bar{r}_0$ = initial mean radius of annular jet at the nozzle exit
(assumed equal to $\bar{a}$)
- r_v = radius of curvature of the annular jet in the vertical plane
- $R = \bar{r}/\bar{r}_0$ = dimensionless mean radius
- t = time
- V = velocity in the tangential direction
- w = half-width of a wedge
- $We = \rho V_0^2 b_0 / 2\sigma$ = Weber number
- x = vertical coordinate
- γ = half-angle of a wedge
- δ = half-angle of the flow spreading
- ϕ = angle of the annular jet velocity vector from the vertical
- σ = surface tension coefficient
- $\tau = g t / V_0$ = dimensionless time
- τ^* = dimensionless convergence time

Subscripts

- o = initial flow conditions at the nozzle exit

ANNULAR LIQUID JET EXPERIMENTS

Myron A. Hoffman* and Ronald K. Takahashi**

1. INTRODUCTION

The quantitative study of annular liquid jets goes back at least to the 1869 paper of Boussinesq [1]. Interest in this subject has been revived recently by Maniscalco, et al. in connection with certain pulsed fusion reactor system concepts [2]. In these fusion reactors, a small pellet containing deuterium and tritium is caused to undergo nuclear fusion through intense compression and heating by lasers, electron beams or ion beams. The products of the pulsed fusion reaction, high energy neutrons, alpha particles and X-rays, as well as the unreacted ions flow toward the reactor vessel, and can do severe erosion damage to the inner wall. In addition, the neutrons can penetrate far into the structure (on the order of a meter or more) and do additional damage [e.g., see Reference 3]. In an attempt to create a self-healing or renewable wall, the idea of placing a vertical annular jet or "waterfall" of liquid lithium about 50 to 70 cm thick and about 10 meters in diameter in the reactor vessel between the fusion pellet and the vessel walls was proposed [2].

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The research described in this paper is primarily experimental and addresses three questions related to the quasi-steady state fluid dynamic behavior of such vertical annular jets during the periods between fusion pulses:

- a) What is the convergence length for closure of the hollow region due to surface tension forces.
- b) Are there any hydrodynamic instabilities which cause breakup of the annular jet?
- c) What is the behavior of the annular jet in passing around a tube or other obstacle (required for transport of laser, electron or ion beams into the pellet region)?

The shape of a typical vertical annular jet flow is shown in Figure 1. The gravity force accelerates the flow in the vertical direction while surface tension forces cause the flow to accelerate inward, tending to close up the hollow space and create a nearly-cylindrical, solid jet. The convergence length, L^* , is defined as the length to closure of the hollow region (see Figure 1).

One of the earliest experimental studies of the convergence length of annular jets which we were able to uncover is that of Binnie and Squire [4]. They studied a small vertical water jet produced by an orifice with a mean diameter of about 0.8 cm and a gap of about 0.32 cm up to velocities of about 2.8 m/s. In 1962, Baird and Davidson [5] studied the various flow regimes possible with vertical annular jets produced by an annular orifice with a mean diameter of 1.24 cm and a gap of 0.029 cm up to velocities of about 2.6 m/s. They also studied the effect of small pressure differences across the annulus on the convergence length. (Both of these papers were uncovered after our research was completed.)

Our original objective was to confirm the scaling laws developed by Hovingh [6] for the large lithium annular jets which predicted convergence lengths of kilometers. Our experiments employed somewhat larger annular water jets than either References [4] or [5] at higher initial velocities up to 10 m/s, thus resulting in a considerable extension of the previous results, as will be described shortly.

An area of research closely related to annular jets is that on water bells. These water bells were often used to determine the surface tension of liquids, and the modern studies of them of some relevance to our present research include the works of Hopwood [7], Lance and Perry [8], G. Taylor [9] and Dumbleton [10]. Water bells are generally produced by the impingement of a round jet on a disk shaped obstruction or on another water jet. The subsequent bell-like shape is influenced by both surface tension and gravity forces. It can be seen that the hollow annular vertical jet is a special case of a water bell with an initial vertical velocity.

The equations for water bells for our particular situation are developed in Section 2, and the theoretical predictions for the convergence length are obtained. In Section 3 the experimental apparatus and measurement techniques are described and the convergence length results are presented in Section 4. Finally, the results of the study of the flow around wedge-shaped penetrations are presented in Section 5.

2. THEORY FOR CONVERGENCE LENGTH

2.1 General Equations for a Nearly Vertical Jet

The general differential equations for a water bell presented by Lance and Perry [8] are based on those of Boussinesq [1]. They are nonlinear and require numerical solution to find the water bell shape for the specified initial conditions. One such numerical method has been provided by Dumbleton [10]. Because of the fact that we have a near-vertical annular jet it is convenient for later discussions to have equations in cylindrical coordinates. Transforming the equations of Ref. [8] from their tangential-normal "natural" coordinate system to our cylindrical coordinate system, we obtain the following vertical and radial momentum equations for a thin jet:

$$\ddot{x} = g - \frac{2\sigma}{\rho b \bar{r}} \sin \phi \cos \phi - \frac{2\sigma}{\rho b \bar{r}_v} \sin \phi \quad (1)$$

$$\ddot{r} = - \frac{2\sigma}{\rho b \bar{r}} \cos^2 \phi - \frac{2\sigma}{\rho b \bar{r}_v} \cos \phi \quad (2)$$

where ϕ is the angle in the vertical plane between the tangent to the jet surface and the vertical (Figure 1), $\bar{r}_v$ is the mean radius of curvature in the vertical plane at a particular axial location, $\bar{r}$ is the local mean radius of curvature in the horizontal plane, b is the local jet thickness, ρ is the liquid density and σ is the surface tension coefficient. By the mean radii, we imply that they are measured at the middle of the jet thickness.

The continuity equation is given by:

$$\bar{r} b \rho V \cos \phi = \bar{r}_0 b_0 \rho V_0 \cos \phi_0 \quad (3)$$

where V is the local total velocity and subscript "o" refers to conditions at the annular nozzle exit (see Figure 1). It should be noted that in these equations the two mean radii of curvature, $\bar{r}$ and $\bar{r}_v$, are assumed to be positive, and the signs of the surface tension force terms are correctly given for these forces acting inward toward the x axis.

Since the radial acceleration is based on the mean jet radius, this implies the assumption of a relatively thin jet such that $b/\bar{r} \ll 1$. This approximation breaks down very near the point of closure as pointed out in Reference [4]. Nevertheless these equations should still give a good approximation to the overall convergence length, L^* .

For our special case of an initially vertical annular jet of sufficiently high velocity such that the angle ϕ is always small (except perhaps very near the closure point), momentum equations are well approximated by

$$\dot{x} = V = V_o + gt \quad (4)$$

$$\ddot{r} = -\frac{2\sigma}{\rho b \bar{r}} - \frac{2\sigma}{\rho b \bar{r}_v} \quad (5)$$

Defining dimensionless time $\tau \equiv gt/V_o$ and dimensionless mean radius $R \equiv \bar{r}/\bar{r}_o$, Equation (5) becomes

$$\frac{d^2 R}{d\tau^2} = -\frac{(1+\tau)}{N_c} \left[1 + \frac{\bar{r}_o}{\bar{r}_v} R \right] \quad (6)$$

where we have defined a convergence parameter:

$$N_c \equiv \frac{g^2 \tau_o^2 b_o^2 \rho}{2V_o^2 \sigma} = \frac{\hat{We}}{Fr^2} \quad (7)$$

and where the Weber number used is based on the jet initial half-thickness:

$$\hat{We} \equiv \frac{\rho v_o^2 b_o}{2\sigma} \quad (8)$$

and the Froude number is based on the initial mean jet radius:

$$Fr \equiv \frac{v_o^2}{g \bar{r}_o} \quad (9)$$

The non-dimensionalized curvature in the vertical plane for a nearly vertical flow is given to good approximation by:

$$\frac{\bar{r}_o}{\bar{r}_v} \approx \bar{r}_o \left| \frac{d^2 \bar{r}}{dx^2} \right| = - \frac{1}{Fr^2 (1+\tau)^2} \left[\frac{d^2 R}{d\tau^2} - \frac{1}{(1+\tau)} \frac{dR}{d\tau} \right] \quad (10)$$

using the relation:

$$\frac{d^2 \bar{r}}{dx^2} = \frac{1}{v^2} \ddot{r} - \frac{g}{v^3} \dot{r}$$

Substituting Equation (10) in Equation (6) yields the final nonlinear differential equation for the near-vertical annular jet:

$$\frac{d^2 R}{d\tau^2} \left[1 - \frac{R}{\hat{We}(1+\tau)} \right] + \frac{R}{\hat{We}(1+\tau)^2} \frac{dR}{d\tau} = - \frac{(1+\tau)}{N_c} \quad (11)$$

It should be noted that the convergence length is related to the nondimensional time to convergence by integrating equation (4):

$$\frac{L^*g}{v_o^2} = \tau^* \left(1 + \frac{\tau^*}{2}\right) \quad (12)$$

2.2 Special Case of High Weber Number Flow

If the Weber number is high enough such that the radius of curvature in the vertical plane is very large, the second and third terms on the left hand side of Equation (11) become negligible. In this limit, the resulting equation is linear and can be integrated twice to yield the nondimensional time to convergence or closure, τ^* :

$$\tau^{*3} + 3\tau^{*2} - 6N_c \left(\frac{dR}{d\tau} \right)_0 \tau^* - 6N_c (1 - R^*) = 0 \quad (13)$$

where $(dR/d\tau)_0$ accounts for any small initial radial velocity component of the jet and R^* is the nondimensional mean jet radius at convergence

$$R^* = \frac{\bar{r}^*}{\bar{r}_o} = \frac{b^*}{2\bar{r}_o} = \sqrt{\frac{b_o}{2\bar{r}_o(1+\tau^*)}} \quad (14)$$

which has been evaluated using the continuity Equation (3).

Using Equation (14) in Equation (13) we obtain a seventh order linear algebraic equation in τ^* which must be solved numerically. One especially tractable limiting case is where $(dR/d\tau)_0 = R^* = 0$; this yields the following cubic algebraic equation:

$$\tau^{*3} + 3\tau^{*2} - 6N_c = 0 \quad (15)$$

Once τ^* is obtained from this equation, L^* can be calculated using Equation (12). Equation (15) was formulated and solved by Hovingh [6] before Lance and Perry's paper [8] came to light. In the above derivation, we have modified Hovingh's original solution for the case of surface tension forces from the inner surface only to the case of surface tension forces from both the inner and outer surfaces. These results will be presented in Section 4.

3. EXPERIMENTAL APPARATUS

The vertical annular jet was produced by using two concentric plexiglas tubes, 85 cm long in an attempt to get a purely vertical initial flow with a known velocity profile. The two tubes were adjusted to be concentric at the exit to within about $\pm 4\%$. The laboratory industrial water supply flowed first through a long horizontal pipe with a standard ASME orifice installed in it and then into a vertical 2" (5.08 cm) diameter PVC pipe about one meter long. The plexiglas tubes were attached to this vertical pipe as shown in Figure 2. A conical transition piece and straightening vanes were installed at the top of the annulus, and two pressure equalizer passages were installed using standard 1/8" (0.32 cm) diameter tubes.

This apparatus produced an annular jet with an initial mean diameter of 4.45 cm and an initial thickness of 0.635 cm with initial jet velocities from about 0.1 to 10 m/s. The diameter to thickness ratio was chosen at about 7.0 to approximate the nominal value for the full-scale lithium jet. The velocity range also covers that proposed for the fusion reactor application.

The orifice plate was calibrated using the standard technique of measuring the time required to fill a large drum, and the calculated velocities were only about 2 to 3% below the ASME calibration curves [11]. The water temperature was measured to $\pm 2^\circ\text{C}$ with a mercury/glass thermometer, which was considered adequate accuracy for determining the water density and surface tension coefficient.

For the higher flow velocities, above about 3 m/s the jet surface was highly turbulent and the hollow region could not be seen through the water. The jet convergence length was then measured by placing a meter

stick next to the jet and measuring to the point of inflection where the jet diameter appeared to become essentially constant. This was checked for a few cases using flash photographs and also using redundant runs, and the agreement was always better than about ± 2 cm in the measured convergence lengths.

For lower velocities below about 3 m/s, the jet surface was transparent enough to see the hollow region, and for these cases the inflection point method was found to agree with the visual observation of the closure point to within about ± 0.5 cm. It should be noted that only below a velocity of about 1 m/s did the jet approach a truly transparent laminar condition. However, there was not a sharp transition to this glassy smooth condition, and the residual surface disturbances were undoubtedly dependent on the upstream disturbances and the nozzle exit smoothness. (The velocity of 1 m/s corresponds to a Reynolds number based on the annular jet hydraulic diameter, $D_h = 2b_o$, of about 1.3×10^4).

4. RESULTS AND DISCUSSION

The experimental results for the two most extensive experimental run series are shown in Figure 3. For run series I, the convergence length increased approximately as expected with increasing jet velocity up to about 1.6 m/s and then behaved as shown in the figure. We hypothesized that the jet was acting as an ejector pump and was reducing the pressure inside the annular region to slightly below atmospheric pressure at the higher velocities in spite of the single pressure equalizer tube installed in the original apparatus. It is estimated that a pressure difference of only about 3 Pa ($\sim 4 \times 10^{-4}$ psi) is sufficient to create a pressure force equal to the initial surface tension forces for our particular jet geometry.

To test our hypothesis, we installed a second pressure equalizer tube (as shown in Figure 2) and reran the high velocity runs. The results were gratifying in that the data seemed to follow the correct trend up to almost 3 m/s. Additional qualitative tests where the pressure equalizer holes were closed off confirmed the strong effect of the pressure difference on the convergence length; for this situation, the convergence length decreased almost to zero. As a final confirmation of our hypothesis, additional tests in a vacuum chamber are planned.

From Figure 3, the experimental results can be seen to follow the trend of the modified Hovingh theory for $R^* = 0$ (Equation 15) very well (up to about 3 m/s as mentioned above), but the data lie about 15 to 25% below this theory. Actually this theory is essentially an upper limit, since it ignores both the finite radius of the jet at convergence, r^* , and the finite radius of the curvature in the vertical plane, r_v . Hovingh's

theory can be corrected approximately for the effect of finite r^* very simply by assuming that the jet velocity is high enough to stay almost constant to the convergence point. Then Equation (14) becomes simply

$$R^* = \sqrt{\frac{b_o}{2r_o}} = 0.378$$

for our jet geometry. This overestimates R^* slightly, but can be seen from Figure 3 to be in excellent agreement with the data (except at very high velocities, of course).

We have also solved the full equations of Lance and Perry numerically [12] and plotted them on Figure 3 as the dashed curve. The difference between the Hovingh theory for $R^* = 0.378$ and Lance and Perry's more exact theory is due to the more accurate solution for R^* and to the effect of the jet radius of curvature in the vertical plane included in the latter. These two effects can be seen from Figure 3 to be quite small for our experimental conditions, and the two theories agree at the higher velocities where these two effects are entirely negligible.

The numerical calculations for our particular nozzle geometry using the version of Lance and Perry's theory given by equation (11) which includes these two effects can be seen to agree much better with experimental data.

In order to show the earlier results of Binnie and Squire [4] and Baird and Davidson [5] along with our data, the nondimensional plot of L^*g/V_o^2 versus N_c shown in Figure 4 has been prepared. It can be seen that all these data tend to follow the same basic trend (except where

pressure differences across our annular jet caused our data to be too low). It should be noted that low velocity data are to the right and higher velocity data are toward the left on this nondimensional plot.

Hovingh's modified theory for $R^* = 0$ is truly a single universal curve on this plot for all nozzle geometries. It can be seen to represent an upper bound to L^* for all the data. The more realistic results for Hovingh's theory with $R^* = 0.378$ (for our nozzle geometry only) shown on Figure 4 can be seen to agree much better with our experimental results. We have not put the exact theoretical results from the integration of Lance and Perry's equations on this figure for the sake of clarity, but it can be seen from Figure 3 that this curve would fall in between the two Hovingh theory curves; it would lie about 10% above the lower Hovingh theory curve at the higher values of N_c (corresponding to lower values of velocity). It should be noted that there is not a single universal curve for any of the theories with finite R^* or finite r_v effects included; that is, each different nozzle geometry will have a different theoretical curve.

Baird and Davidson present their own integrated theoretical results for Boussinesq's theory for their particular nozzle geometry and a finite $r^* = 0.16$ cm ($R^* = 0.258$). A nondimensionalized version of their "accurate" theoretical results is shown by the dashed curve on Figure 4. It can be seen to agree reasonably well with their experimental results.

Binnie and Squire developed their own approximations to the basic Boussinesq equations which they also solved numerically for their nozzle and plotted in their paper. We have nondimensionalized their "rigorous" results and presented them as the dotted curve on Figure 4. Their theoretical result includes a finite $r^* = 0.251$ cm ($R^* = 0.632$), but the

agreement with their data is only fair, particularly at the lower velocities (data points on the right) where they had some difficulty suppressing an initial divergence of their annular jet flow.

From Figure 4, it can be seen that our experiments have extended the confirmation of the convergence theories by over three orders of magnitude in N_c . However, the region of interest for the large radius and large thickness lithium annular jet is still far to the right near values of N_c typically on the order of 10^4 . The corresponding convergence lengths predicted by both Hovingh's and Lance and Perry's theoretical results are many kilometers. As a result, there seems to be no possibility that the large annular lithium jet will converge appreciably within the 10 to 15 m height of the reactor.

The second question of great importance for the fusion reactor application is whether or not any hydrodynamic instabilities develop which could cause the annular jet to break up in fall lengths on the order of one or two diameters. In the presence of the "natural" disturbances due to jet turbulence and the laboratory environment (building vibrations, etc.), we saw no evidence of breakup for fall lengths of almost seventy diameters. We have also run some initial qualitative experiments with forced excitation using pulsed air jets around the outer circumference of the annular jet as it exits from the plexiglas tubes. Axisymmetric waves which travelled down the jet were observed, but no signs of breakup were seen. Further experiments in this area are planned.

5. PENETRATION STUDIES

The third question listed in Section 1 which we studied is related to the necessity of penetrating the annular jet in order to get laser, electron or ion beams into the central region where the fusion pellet is to be irradiated. We assumed that the penetration would be streamlined on top and we simulated this streamlining by simple wedges of half angle γ , as shown in Figure 5. The wedges penetrated all the way through both sides of the annular jet, which simulates two beam tubes facing one another reasonably well.

At very low velocities with very small objects, it has been observed that a liquid can flow around the surface of a curved body. This has been called the teapot (and also the Coanda) effect and one plausible explanation is given in Reference [13]. We too observed this effect when we inserted small wires (typically less than a millimeter in diameter) into the annular jet at very low flow velocities (well below one meter per second) where the flow would often rejoin at the bottom of the wire. However, we have made no systematic study of this phenomenon because it is not in our present range of interest.

We were interested in investigating the effects of rather large penetrations at velocities above 1 m/s. Typical ratios of the wedge half-width to the mean radius of the annular nozzle, $w/\bar{a}$, of 0.14, 0.28, and 0.57 were studied over a range of wedge half angles, γ , from about 23° to about 72° . A flash photograph of a typical flow over such a wedge is shown in Figure 6. It can be seen that the flow has a complex three-dimensional form with momentum effects appearing to dominate the flow spreading or splitting below the wedge.

From flash photographs of the head-on view of the flow, such as sketched in Figure 5a, the total flow spreading angle, $2\hat{\alpha}$, was measured 2.5 cm below the wedge with an estimated accuracy of $\pm 2^\circ$. These results are semi-quantitative, but they can be considered to be indicative of the spreading angles to be encountered in practice.

Results for three families of wedges with three different values of $w/\bar{a}$ are shown in Figure 7 for the lowest velocity investigated systematically, 1.45 m/s. (A typical family of wedges with constant $w/\bar{a}$ is produced as shown in Figure 5c.) Dashed lines have been added to Figure 7 only to aid the eye in following the trends in the data points.

It appears impractical to try to develop a theory for the actual three-dimensional flow. However, the theory for a two-dimensional sheet jet flow of finite thickness impinging on a wedge has been solved in the potential flow approximation by Siao and Hubbard and their results are reported in References [14] and [15]. These theoretical results, taken from the figures in the above two references, have been replotted on Figure 7 for two cases, $w/\bar{a} = 0.30$ and 0.50 . (The two-dimensional sheet jet geometry is described in Figure 5b.)

It can be seen from Figure 7 that the flow spreading angle for our complex 3-D flow tends to agree with the ideal 2-D jet theory at the smaller wedge angles for this moderate flow velocity of 1.45 m/s. This seems to confirm that momentum effects dominate the flow. At the larger wedge angles the 3-D effects tend to increase and evidently cause the flow spreading angle to tend to level out, probably because the 3-D effects allow the flow to spread along the wedge as well as split sideways (see Figure 6).

The effect of jet velocity is shown in Figure 8 for one family of wedges with a constant $w/\bar{a} = 0.28$. As the velocity is increased, the departure from the ideal 2-D sheet jet theory can be seen to occur at lower and lower wedge angles. This again is attributed to the 3-D effects, since these effects tend to become more dramatic as the velocity is increased as can be imagined looking at Figure 6.

6. CONCLUSIONS

This experimental study has provided considerable insight into the fluid dynamic behavior of vertical annular jet flows. The answers to the three basic questions posed in Section 1 can be summarized as follows:

- a) The experiments on convergence length tend to confirm that the modified theory of Hovingh with a finite jet radius at convergence is probably an adequate scaling law to use for extrapolation to larger annular jets. More exact predictions of the convergence length can be obtained by numerical integrations of equation (11) or Lance and Perry's equations, if desired. As far as the fusion reactor application is concerned, there appears to be no possibility that the lithium annular jet will converge appreciably for the proposed reactor flow conditions.
- b) No hydrodynamic instabilities in the annular jet flow due to the naturally occurring disturbances in our experiments have been observed for fall lengths of almost seventy diameters. However, carefully planned experiments with rather large amplitude forced excitation are necessary to resolve the question of annular jet stability in the fusion reactor environment.

- c) When a wedge-shaped obstacle is placed in the path of the annular jet, a complex, three-dimensional flow pattern results. However, at low jet velocities up to about 1.5 m/s and for small wedge half angles up to about 20° , the flow spreading or splitting angle agrees reasonably well with the ideal potential flow solution for a two-dimensional sheet jet; from this we can infer that momentum effects dominate the flow spreading. It is clear from these results that auxiliary jet flows will be required to fill in these inverted V-shaped openings created by the proposed beam transport tubes in the fusion reactor application.

REFERENCES

1. Boussinesq, J., Comp. Rend. Acad. Sci., (Paris), 69, p. 128 (1869).
2. Maniscalco, J. A., Meier, W. R., and Monsler, M. J., "Conceptual Design of a Laser Fusion Powerplant", UCRL-79652, Lawrence Livermore Laboratory, July 14, 1977.
3. Hovingh, J., "First Wall Response to Energy Deposition in Conceptual Laser Fusion Reactors", UCRL-77588, Rev. I, Lawrence Livermore Laboratory, February 1976.
4. Binnie, A. M. and Squire, H. B., "Liquid Jets of Annular Cross-Section". The Engineer, 171, pp. 236-238, (London) April 11, 1941.
5. Baird, M. H. I. and Davidson, J. F., "Annular Jets, Part I, Chem. Engr. Sci., 17, pp. 467-472, 1962.
6. Hovingh, J., "Stability of a Flowing Circular Annular Liquid Curtain", Internal Memo SS&A-77-108, Lawrence Livermore Laboratory, August 8, 1977.
7. Hopwood, F. L., "Water Bells", Proc. Phys. Soc., B65, p. 2-5, (London, 1952).
8. Lance, G. N. and Perry, R. L., "Water Bells", Proc. Phys. Soc., B66, pp. 1067-1072, (London) 1953.
9. Taylor, Sir G., "The Dynamics of Thin Sheets of Fluid, Part I - Water Bells", Proc. Royal Soc., 253, pp. 289-295, (London) 1959.
10. Dumbleton, J. H., "Effect of Gravity on the Shape of Water Bells", J. Appl. Phys., 40, No. 10 pp. 3950-3954, 1969.
11. ASME, Flow Measurement, Power Test Codes Supplement, Ch. 4, Pt 5, 1959.
12. Takahashi, R. K., "Experimental Investigation of the Stability of Liquid Sheet Jets", M.S. Thesis, Department of Mechanical Engineering, University of California, Davis, December 1978.
13. Reiner, M., "The Teapot Effect - A Problem", Physics Today, pp. 16-20, September 1956.
14. Robertson, J. M., Hydrodynamics in Theory and Application, Prentice-Hall (Englewood Cliffs, N.J.) 1965.
15. Yih, C. S., Fluid Mechanics, McGraw-Hill (N.Y.) 1969.

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Figure Titles

- 1 Cross-section of a near-vertical, hollow annular jet showing the key parameters involved in the solution for the closure or convergence length, L^* .
- 2 Cross-section of the concentric plexiglas tube apparatus used to produce the annular jet.
- 3 Comparison of the experimental results for convergence length with three theoretical models with differing degrees of exactness.
- 4 Nondimensional presentation of the experimental convergence length data from three different experiments and comparison with theory.
- 5 Geometry of the wedge penetration experiments in the annular jet and comparison with an ideal 2-D sheet jet geometry.
- 6 Typical experimental flow pattern around a wedge-shaped obstacle penetrating through both sides of the annular jet showing the 3-D nature of the flow.
- 7 Experimental flow splitting or spreading angle for three families of wedges at a relatively low flow velocity of 1.45 m/s and comparison with the ideal 2-D sheet jet theory.
- 8 Effect of flow velocity on the flow spreading angle for a single family of wedges with $w/a = 0.28$.

Fig. 1 Cross-section of a near-vertical, hollow annular jet showing the key parameters involved in the solution for the closure or convergence length, L^* .

Figure 2 Cross-section of the concentric plexiglas tube apparatus used to produce the annular jet.

Figure 3 Comparison of the experimental results for convergence length with three theoretical models with differing degrees of exactness

Figure 4 Nondimensional presentation of the experimental convergence length data from three different experiments and comparison with theory.

(a) Geometry for Annular Flow Experiments

(b) Geometry for 2-D Sheet Jet Theory

Same w (and $w/\bar{a}$) wedges

(c) Method for Variation of Wedge Angle

Figure 5 Geometry of the wedge penetration experiments in the annular jet and comparison with an ideal 2-D sheet jet geometry

Figure 6 Typical experimental flow pattern around a wedge-shaped obstacle penetrating through both sides of the annular jet showing the 3-D nature of the flow.

Figure 7 Experimental flow splitting or spreading angle for three families of wedges at a relatively low flow velocity of 1.45 m/s and comparison with the ideal 2-D sheet jet theory.

Figure 8 Effect of flow velocity on the flow spreading angle for a single family of wedges with $w/a = 0.28$.