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THE LITHIUM FALL REACTOR CONCEPT— THE QUESTION OF JET STABILITY, WITH RECOMMENDATIONS FOR FURTHER EXPERIMENTS

S. W. Kang

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LAWRENCE LIVERMORE LABORATORY

University of California Livermore, California 94550

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THE LITHIUM FALL REACTOR CONCEPT— THE QUESTION OF JET STABILITY, WITH RECOMMENDATIONS FOR FURTHER EXPERIMENTS

ABSTRACT

The stability of a liquid-lithium jet flow is of importance in a laser fusion reactor design. In this report we analyze and discuss jet stability with respect to fluid dynamics, delineating physical factors that may affect the jet breakup and performing some simple calculations to determine quantitatively the relative influences of various parameters. We define areas of uncertainty and recommend possible experimental verification, theoretical analysis, or both.

INTRODUCTION

One design for a laser fusion power plant includes the promising liquid-lithium "waterfall" concept, whose principal feature is a thick, continuously recyclable, falling sheet of lithium in the reactor. This "first wall" is intended to reduce neutron damage to the blanket structural materials, absorb most of the released energy, and also serve as the primary coolant and fertile material for tritium-breeding.

While this concept has many advantages, it poses some thermodynamic and fluid-dynamic uncertainties. At question are the stability of the liquid-lithium jet, the effects of a microexplosion on the jet, reassembly of the waterfall if necessary, possible condensation behavior of the lithium vapor, and the vibration/oscillation effects of the reactor housing on the flow characteristics.

Steady flow of the intact liquid jet is believed to be an essential condition for the energy absorption, for shielding, and for tritium production. Thus we examine only the stability question in this initial report. Specifically, we discuss the salient features of the liquid lithium flow under the following design conditions: a chamber pressure of 10^{-1} Torr, a temperature of ~ 800 K, a chamber radius of 5 m, a jet thickness of ~ 60 cm, and jet velocity of 10 m/sec. Other design aspects may be found in the reports by Maniscalco¹ and Meier and Maniscalco.² We attempt here to (a) delineate the important physical parameters, (b) estimate the quantitative stability criteria by performing some brief analyses, and (c), where uncertainties exist, recommend appropriate experiments or alternative designs.

The author emphasizes that this is a very preliminary analysis of the fluid-dynamic and thermodynamic aspects of the liquid waterfall concept. The literature survey is only a cursory look at the state-of-the-art on

the stability analyses. Only the flow characteristics relevant to the jet-integrity analysis are investigated in detail. Therefore, only the papers relating to that subject are cited in the text. However to gain a broader perspective on the general subject of jet-flow phenomena, see works by Pai,³ Rajaratnam,⁴ Abramovich,^{5,6} and Levich.⁷ We plan further reports on other fluid-dynamic aspects of laser fusion power generation.

Stability of the Liquid Jet

Breakup of a liquid jet begins when increased surface area renders the jet unstable. The process by which this phenomenon occurs depends on the nature of the flow in the container. Some of the variables are: whether the flow is laminar or turbulent, the way in which energy is imparted to the liquid, the physical properties of the liquid, and the properties of the ambient atmosphere. In general, the degree of jet breakup increases with increasing jet velocity and ambient density, and decreases with increasing nozzle diameter, jet viscosity, and surface tension.⁸ We wish to quantify these observations in order to establish whether planned reactor configurations will provide an adequate liquid-lithium jet flow.

Numerous analyses—both theoretical and experimental—exist in the literature concerning the flow phenomena where a laminar-flow regime is in effect. By contrast, relatively few papers treat the turbulent-flow regime. Although there are some clear distinctions between laminar and turbulent flow cases, some commonalities also do exist, especially in jet-breakup cases. Therefore, results of laminar analyses may be of value in considering turbulent-jet phenomena in a

reactor. Also, future modifications in reactor design may introduce laminar jets. In addition, the flow characteristics of both the circular-jet disintegration and of the sheet-jet breakup will be considered in this report. We note in passing that there are three modes of disintegration for a sheet of jet, i.e., from the rim, through perforation, and due to the amplifying waves at the liquid surface (see Dombrowski and Fraser¹⁰).

Also of great interest are the separate effects of various parameters on the jet-breakup phenomena. These are:

- "Nozzle/liquid" parameter, known as the Ohnesorge number (Z).
- Ambient condition μ , or ρ . (ρ = density, p = pressure).
- (Relative) jet-velocity effects.
- Nozzle-configuration effect.
- Flashing/cavitation effect, e.g., superheated "dwell time."
- Fluid-property effect, e.g., μ , σ (μ = viscosity, σ = surface tension).
- Vibration/oscillation effect.

In view of the desirability of considering these effects as well as the laminar/turbulent jet-flow aspects, discussion shall follow both courses. We present first the various jet breakup mechanisms as the flow changes from laminar to turbulent; next we discuss the individual effects of the physical parameters on the disintegration of a jet, which may be laminar or turbulent and which may be circular or a flat sheet. It is believed that, in this way, the complex interaction of the jet-disintegration parameters is fully described.

Laminar and Turbulent Flows

In laminar jet flows, the governing physical mechanisms are the capillary (surface-tension) forces, and the aerodynamic forces as the jet velocity increases. Grant and Middleman¹⁰ observed that the intact length of a liquid jet increases at first linearly (the laminar regime) with velocity. This was predicted by Weber,¹¹ who extended Lord Rayleigh's inviscid analysis to the viscous case.¹² As the jet velocity is increased further, the liquid jet intact length reaches a maximum and then decreases (see Fig. 1). A transverse wave disturbance has also been observed in addition to the axisymmetric waves. The physical mechanisms causing the peak and the subsequent reduction in the intact length of the jet are aerodynamic forces and the increase in the level of the initial disturbances within and at the exit of the nozzle (see Phinney^{13, 14} and Fenn and Middleman¹⁵).

As the jet velocity increases further, the flow is now in the turbulent-flow regime and the intact length increases again. However, the jet velocity is now so great that the breakup time, $\Delta t \sim X_{ij}/V_j$, is usually less than that for some laminar velocities. The surface tension, the viscous ambient effect (which reduces the relative velocity at the jet surface), and the "elastic" behavior of the liquid at the surface inhibit the growth of the disturbances. More details on these general interpretations may be found in work by Davies, with others,^{16, 19} Townsend,²⁰ Phinney,²¹ and Dunn.²²

The flow of a liquid sheet is the subject of a report by Dombrowski and Fraser,⁹ Fraser, et al.,²³ and Dombrowski and Munday.²¹ For the turbulent-flow case, they find that the surface of the sheet becomes ruffled with cavities and ridges. At high injection velocities aerodynamic waves predominate and the sheet disintegrates. When turbulence is produced at low velocities, for example, with large orifices, local depressions in the surface will tend to perforate the sheet in thin enough region before aerodynamic waves grow to sufficient amplitude. Where ambient effects are expected to be small, such as flow into a vacuum, turbulent sheets always disintegrate through these perforations.²¹ Comparison of turbulence criteria shows that liquid sheets are significantly more stable than plain jets issuing from orifices of the same area. Furthermore, the claim is made in Ref. 23 that, in the case of liquid sheets, turbulence plays only a minor role and does not appear to enhance the atomization process to any significant extent, either in vacuum or in atmosphere. These above experiments and analyses were for the Reynolds numbers ($N_{Re} = LV\rho/\mu$) in the range of 10^4 – 10^5 . Few tests have been performed for jets with the Reynolds number in the range of 10^6 . These magnitudes are usually obtained with very high velocities, for example, in rock-cutting, usually in 100–300 m/sec, with the resultant atomization and stripping phenomena at the jet surface. In terms of the jet-stability analysis, some physical distinctions appear for the same Reynolds number but with different orifice sizes and velocities.²⁴

Thus there is little agreement in the literature cited on the dominant physical mechanisms of turbulent jet breakup, especially in terms of quantitative predictions. Estimation of the intact length of a jet in a turbulent-flow regime therefore constitutes one of the uncertainties in the reactor design with a Reynolds number well in excess of 10^6 .

Given this uncertainty, however, there is much information we can obtain from these previous investigations and by performing some approximate analyses. Because the present design is not finalized, there is justification for looking into the separate physical parameters of jet-breakup behavior. Discussion of these various influences follows.

Fig. 1. Jet-breakup curve. The degree of liquid breakup is shown as a function of intact jet length (X_B), nozzle exit diameter (D), and jet exit velocity (V_j); the upper diagram gives a visual representation of liquid breakup (p = pressure, ρ = density).

Parameter Effects

As previously mentioned, there are various physical parameters that influence the jet-breakup behavior. The factors that will be considered here are: ambient conditions, "nozzle/fluid" conditions, nozzle-configurations, fluid-properties, "cavitation," and nozzle-vibrations.

Ambient Effects. The aerodynamic forces in the surrounding gases act on the jet surface in such a way that under certain conditions they tend to amplify any wave disturbances at the interface and promote jet disintegration. Theoretical analyses using perturbation

techniques for a circular jet (see, for example, Ref. 7, p. 643) indicate that the jet is unstable for wavelengths greater than $(2\pi\sigma)/(\rho_z V^2)$ and that the intact jet length would be approximately thirty times the jet radius. For the present case of a lithium vapor at say, $p_a = 0.1$ Torr, $T_a \sim 800$ K, $\sigma \sim 400$ dyne/cm, we calculate that the minimum wavelength for which an unstable jet would result is approximately equal to $2 \cdot 10^4$ cm, a very long wavelength. Thus it would appear that jet breakup would be rather insensitive to the ambient effects.

Experiments performed for the ambient effect on jet breakup by Fenn and Middleman¹⁵ and Phinney¹⁴ demonstrate that greater ambient pressure (or density) tends to reduce the intact breakup length, as shown schematically in Fig. 2. As ambient density is decreased, the intact length increases up to a certain value and remains unchanged. Fenn and Middleman found the numerical value for the critical condition below which the ambient effect no longer exists. It is expressed as:

$$(We_c)_{crit} \approx 5.3$$

where the ambient Weber number is defined to be $We_c = (\rho_a V_j^2 D) / \sigma$.

Fig. 2. Effect of ambient conditions on intact liquid jet length.

Substitution of appropriate values for our reactor design in the Weber number expression yields 10^{-3} , which is much less than 5.3. We again may infer that the ambient effect on a jet from a circular nozzle is not significant.

"Nozzle/Fluid" Effects. The term "nozzle/fluid" signifies the interactive effects of the liquid's fluid property and the nozzle dimension. It is defined to be

$$Z = \frac{\mu_l}{\sqrt{\rho_l \sigma D}}$$

and is commonly called the Ohnesorge number. This number, which can also be expressed as a ratio of $(We_l)^{1/2}$ to Re_l , denotes in physical terms a measure of the relative importance of viscosity and surface tension in controlling stability. To be more specific, its magnitude has been found by Grant and Middleman,¹⁶ by

Phinney,^{13, 21} and by Lienhard and Day²⁵ to affect the intact jet length as shown in Fig. 3, the critical transition Reynolds number (Fig. 4), and the initial disturbance level in or near the nozzle (Fig. 5). Although the experiments were not performed for the Z value of interest, i.e., $Z \approx 10^{-4}$, reasonable extrapolation may be made to show that at such a low value of the Ohnesorge number, the breakup length in the laminar range increases, delays the transition to the turbulent regime, and is able to accommodate greater initial disturbance before breakup. In other words, the parameter Q used in Fig. 4 and first introduced theoretically by Weher¹¹ can be interpreted to contain only X_B/D (X_B = intact jet length, D = nozzle diameter) and $(We_l)^{1/2}$, since $1 + 3Z$. In the present case (We_l , Weher number, is defined as $(\rho_l V_j^2 D) / \sigma$). This report will also show that the results obtained by Phinney²¹ are of great use in utilizing such a small value of Z for the present condition of a thick liquid-lithium jet flow.

Fig. 3. Nozzle/fluid effect on breakup length. The Ohnesorge number, Z , is defined as $(We_l)^{1/2} / Re_l$.

Fig. 4. Dimensionless correlation of jet breakup. ($Q = (X_B/D) / (1 + 3Z)(We_l)^{1/2}$).

Fig. 5. Variations in initial-disturbance levels.

Nozzle-Configuration Effects. Figure 6 describes one effect of the orifice inlet length on the intact liquid jet length as observed by Grant and Middleman¹⁰ for the laminar case. Physically there exist different patterns of the jet velocity profiles depending upon the nozzle-exit configuration. Moreover, the jet must undergo "relaxation" from a no-slip wall condition at the nozzle exit to a more or less uniform profile farther downstream. The viscosity would affect this transitional behavior at the interface, especially in the turbulent-jet case. Appropriate tests have not yet been performed for our proposed configuration. The author is making continuing analyses to better understand and determine the extent of its influence on the jet-breakup behavior.

Fig. 6. Nozzle-configuration effect on jet breakup.

Fluid-Property Effects. By fluid-property effects we mean the change in the intact jet length for different fluids and for different property values. Although a majority of experiments has been with water under atmospheric conditions, other substances have been similarly tested such as fuel, silicone oil, mercury and even some viscoelastic materials.^{19, 23, 26-28} Viscoelastic

(also called non-Newtonian) fluids in general more readily amplify the disturbances, but the jet transforms itself into long threads without breaking into droplets, which is the case for Newtonian fluids. One unifying factor for these seemingly disparate fluids is that jet breakup behavior may be correlated in many cases in terms of dimensionless parameters for meaningful physical interpretation. Although no data or analysis has been found for lithium, we believe, based on the above observation, that reasonable quantitative prediction can be made for a lithium jet by application of results obtained for other fluids with differing properties.

Flashing/Cavitation Effects. Liquids moving isothermally from a given pressure zone to a low-pressure ambience may cross the bubble-point curve, attaining final equilibrium wholly or in part as a vapor. This behavior forms the basis for flash evaporation, and its influence may be present in the disintegration of the liquid lithium jet (or sheet) into drops and vapor. Investigations relevant to this problem have been made by Lienhard and Stephenson,²⁹ Brown and York,³⁰ and Lienhard and Day,²² among others. The latter work, concerned primarily with the effect of the liquid superheat on the bubble nucleation/growth within the jet and possible breakup of the liquid mass, will be applied to the reactor design in question. A convenient parameter is the time required for the bubble nucleation/growth/jet disruption for a given degree of overpressure (or superheat). If this time is greater than the liquid transit time in the reactor housing, then we conclude that the flashing effect is negligible on the jet breakup. For the present reactor design the overpressure of 1 Torr or less and the growth time based on Eq. (18a) of Ref. 25 is approximately 10^{-3} sec, whereas the travelling time of the liquid lithium jet is about 1 sec. Thus we believe that the flashing effect on the jet breakup is not significant.

Vibration/Oscillation Effects. The possible undulation of the liquid jet leaving the nozzle may originate from the vibration of the reactor housing upon impingement of shock waves initiated by the pellet micro-explosion. Should such a phenomenon occur, the duration of such disturbances is estimated to be about 1 msec. We wish to determine the effect of such an input to the jet housing (nozzle) on the jet behavior upon discharge into the reactor chamber.

Analysis of this nature is complicated by the consideration of possibly large initial disturbance levels, encompassing broad range of frequencies, etc. This constitutes another uncertainty in the present turbulent-jet problem. In the present report, an estimation will be made treating the vibration problem as a disturbance introduced to the liquid-jet surface at the nozzle exit with a given frequency and disturbance level. Resonant behavior of the liquid sheet with trapped air has been investigated by Binnie.^{31, 32}

For the liquid-mass velocity (V) of 10 m/sec, say, we may express the frequency of the disturbance (f) in terms of wavelength (λ); i.e.,

$$\lambda = \frac{V}{f} = \frac{10^3}{f}$$

Thus we have $\lambda = 1$ cm for $f = 10^3$ cps and 10^2 cm for $f = 10$ cps. We now determine whether such a range of wavelengths would cause amplification of the disturbances at the liquid surface and resultant breakup of the jet. As calculated and noted earlier in the consideration of the ambient effects on circular jets, the destabilizing wavelengths using Levich's equation⁷ for the present conditions are 10^1 cm or greater. Comparison with the present disturbance wavelengths shows that the circular jet will be stable. For the case of liquid-sheet flows, the studies made by Squire,³¹ Hagerty and Shea,³² and Dombrowski and Cooper³³ are used here, recognizing the laminar nature of their analyses. Phinney^{21, 36} claims the existence of some equivalence between the laminar-flow disturbances and the turbulent-flow disturbances, on the basis of correlatability of available empirical data. In any event, application of the stability criteria yields the result that for the sheet flow into the ambient vapor-lithium density of 10^{-7} g/cm³ (corresponding to $p_v = 0.1$ Torr) the disturbance frequency introduced at the nozzle should be less than 0.1 Hz, a seemingly unlikely event. We thus conclude that introduction of oscillating disturbances at the nozzle exit will not result in jet breakup, based on the perturbation analysis of a regular, low-velocity sheet flow. It should be reiterated that the effect of vibrations of the reactor housing on the jet-sheet behavior is not yet clearly delineated.

Tentative Estimate of the Jet-Breakup Length

Having considered separately the effects of various physical parameters on the jet disintegration, and recognizing the far-from-understood nature of the turbulent-jet breakup phenomena, we may make an estimate of the intact jet length based on Phinney.³⁶ However, quantitatively as well as qualitatively, the estimation may be inaccurate. We shall discuss this subject further in this report. Essentially, we believe a plateau exists with respect to the Reynolds number in the turbulent case (as in the laminar case). This finding is also made by Kusui.³⁷ For $(We_j)^{0.5} > 25$, he proposes a correlation of the intact length as follows:

$$\frac{X_B}{D} \sim 55 + 1.085 (We_j)^{0.5}$$

For the case of liquid lithium, by substituting the various values for its properties we have $We_j = 4(10^3)$. Therefore,

$$\frac{X_B}{D} = 273, \text{ or } X_B = 82 \text{ m.}$$

This intact-jet length far exceeds 10 m, the design jet-length in question.

Although this empirical correlation appears to yield a stable-jet length adequate for present purposes, caution is advised in accepting it as definitive and as applicable to other turbulent, circular jet cases. The author's experiments did not encompass the full range of other physical parameters such as nozzle length and nozzle exit angles, etc. Indeed, Kusui³⁷ notes changes in the intact length due to variations in these parameters. We believe these factors would combine to produce other velocity profiles and turbulence intensities at the nozzle exit, thus affecting jet intact length. No measurements have yet been made of the resulting turbulence intensity or velocity profiles.

Figure 7 shows the quantitative results of Phinney³⁶ using variations in jet velocity and the nozzle diameter. The figure also shows a group of Reynolds numbers up to $5(10^3)$, the probable limit of Phinney's correlation. The reactor design being studied calls for the Reynolds number well over 10^5 . Thus our preceding calculation of the intact-jet length requires an extrapolation from Phinney's work. This lack of empirical data demonstrates the need for further investigations.

Possible Experiments and Future Work

In view of statements made throughout the text concerning the many uncertainties involved in an accurate prediction of an intact length of a liquid lithium jet, it seems appropriate to review these uncertain areas and to consider possible approaches to resolve these questions. Some of the more important areas are listed below.

Applicability to Lithium Case. This involves the question of whether experiments performed on other fluids such as liquid water are applicable to liquid metals like lithium. There seem to exist no intrinsic differences between other liquids and lithium, so that dimensionless correlations based on other liquids (chiefly water) are reasonably valid also for liquid lithium. Moreover, a similar liquid metal, mercury, has been tested by Dombrowski and Fraser³ and was found to correlate well with the results of the liquid water.

Fig. 7. Intact length of turbulent jets of liquid lithium.

Nevertheless, it would be desirable to conduct some simple experiments using liquid lithium in a well-correlated region, say, laminar flow, and ascertain whether any anomaly exists for lithium-jet flows. This question is not considered to be as crucial as other uncertain areas.

Very High Reynolds Number. The present design calls for the Reynolds number in the 10^6 range, and there is a paucity of analyses—theoretical or experimental—of turbulent-jet breakup phenomena at such large Reynolds numbers. Some of these are the works by Lienhard and Day²⁵ which use numbers up to $Re_j = 2(10^5)$; by Dunn,²² up to $Re_j \sim 6(10^5)$; and by Semerhan et al.,³⁸ up to $Re_j \sim 7(10^5)$. The irregular nature of the turbulence phenomena at the jet surface, especially in the first few diameters of the nozzle exit, makes it plain that it would be difficult to obtain any consistent picture of the physical processes involved in the liquid-surface breakup. However, a common feature of these analyses is that rather high jet velocities are involved, e.g., velocities of 500 m/sec have been used in the Soviet works of Semerhan et al.³⁸ This implies in most cases rather small nozzle-diameter sizes, the net result being suspected high velocity and pressure fluctuations in the jet and enhanced entrainment of the ambient vapor.¹⁷ On the other hand, when the Reynolds number is large because of a large orifice dimension, we expect smaller magnitudes in these fluctuations and smaller penetration of the turbulent eddies into the interior of the liquid surface.^{7, 18}

Experiments are needed in which the Reynolds number is of the order of 10^6 with the jet velocity being reasonably small but with rather large characteristic dimensions. For example, for a liquid water in atmospheric conditions, a characteristic length of 10 cm would produce a Reynolds number of 10^6 for the jet velocity of 10 m/sec, a seemingly realizable condition in the laboratory. In this connection, we note that the ranges of the Weber number of interest have already been tested and thus are considered correlatable.

"Vacuum" Effects. The designed ambient condition of the vapor lithium in the reactor chamber at 0.1 Torr or less poses a question for us as to the possibility of the liquid jet behaving abnormally compared to that under atmospheric condition, such as flashing. Although a liquid sheet has been observed to display a more placid behavior in vacuum because of the disappearance of the ambient effects,²⁴ it is not clearly understood whether the low-density effects are minimal on the breakup behavior of the present turbulent liquid-lithium jet. Experiments of the jet flows under evacuated conditions would be useful.

Shape Effect. Behavior of a circular jet contrasts with that of a liquid sheet when subjected to disturbances at the surface. For example, in laminar flow, only axisymmetric disturbances with wavelengths greater than the circumference have been observed to cause breakup in a circular jet.^{11, 12} In a sheet flow both symmetric and antisymmetric disturbances produce instability of the jet in some cases.³³⁻³⁵ Also, the effect of surface tension in the case of a sheet flow is to effect shrinkage in the liquid sheet. In the present case of an annular-sheet flow, surface tension may affect jet-breakup behavior. An analysis or experiments, or both, in this connection would be helpful.

Vibration/Oscillation Effect. This particular concern stems from the speculated impingement of shock waves generated by the pellet microexplosion resulting in a vibrating reactor housing, which would, in turn, introduce initial disturbances at the nozzle. Although we noted earlier that the inferred wavelengths may be such that the disturbances are not destabilizing, this conclusion is not entirely established. Future experiments should be constructed to analyze this uncertainty.

Energy Absorption Effect. Currently it is unknown whether the pellet microexplosion will cause the liquid lithium jet to disintegrate or to remain intact. Some testing procedure should be found to answer this question. A useful beginning would be the effect of shock waves on a sheet, as in the work of Priem,³⁹ who found that the reflected shock waves cause considerably more disruption than the incident shock waves.

Jet-Reassembly Question. Should experiments show the liquid jet to be dispersed, we wish to know whether the incoming liquid jet will be discharged into the now highly dispersed reactor chamber and then reconstitute itself as a stable, intact jet. We will make further analysis of the transient flow of a liquid jet, and some physical insight might be obtained from the experiments of Bowden and Brunton.⁴⁰

Interface Velocity Effect. Marked stability was observed with increased viscosity for the liquid-jet flow.^{7,9, 11} The reduced relative velocity at the liquid-jet interface due to viscosity is attributed to retard destabilization.¹⁴ Experimental measurements of this effect would be difficult to make; however, some approximate theoretical analysis can be made, and the author is investigating this.

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