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JET STABILITY IN THE LITHIUM FALL REACTOR

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A preliminary analysis has been made of the various hydrodynamic aspects involved in the stability of a liquid-lithium jet in a laser-fusion reactor, which comprises a part of LLL's laser fusion power-generation concept. Various physical factors that may affect the jet breakup are delineated, and some approximate calculations are performed to determine their relative influences. Areas of uncertainty are pointed out, along with plans for experimental verification or further theoretical analysis.

INTRODUCTION

One of the promising laser-fusion power plant designs is the liquid-lithium "waterfall" concept. Its principal feature is a thick, continuously recyclable first-wall of lithium in the reactor which would hopefully reduce the neutron damage in the blanket structural materials, absorb majority of the fusion energy, and also serve as the primary coolant and fertile material for tritium breeding.

While this concept seems to be quite promising, it contains some uncertainties from a thermo- and fluid-dynamic point of view. These concerns include the stability of the liquid-lithium jet, effects of a micro-explosion on the jet, reassembly of the waterfall, possible condensation behavior of the lithium vapor, and the vibration/oscillation effects on the flow characteristics.

The stability question will be treated in this paper. Specifically, we shall discuss the salient features of the liquid-lithium flow phenomena under the present design conditions, i.e., the chamber pressure of $10^{-1}$ torr, the temperature of 800 K, the chamber radius of 5 m, the jet thickness of 60 cm and its velocity of 10 m/sec. Other design aspects may be found in the papers by Maniscalco, Meier and Monsler and Meier and Maniscalco. We shall attempt to: (a) delineate the important physical parameters, (b) estimate the stability criteria by performing some simple calculations, and (c) where uncertainties exist, recommend some areas which may be simulated by experiments or some alternative design configurations to help reduce these uncertainties.

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THE JET/SHEET STABILITY PROGRAM

A. General Description

The basic physical principle of liquid breakup consists in increasing the surface area until it becomes unstable and disintegrates. The process by which this phenomenon takes place depends upon the nature of the flow in the container, i.e., 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. We wish to quantify these qualitative observations in order to establish whether or not the planned reactor configurations provide an adequate liquid-lithium jet flow.

Also of great interest for present purposes are the separate effects of various parameters on the jet-breakup phenomena. Thus we present first the various 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.

B. Laminar and Turbulent Flows

In laminar jet flows the governing physical mechanisms are the capillary (surface-tension) forces, and, as the jet velocity increases, the aerodynamic forces (in the form of a dynamic pressure) also exert influence on the liquid-jet surface phenomena. Observations show—see, for example, Grant and Middleman—that the intact length of a liquid jet increases at first linearly (the laminar regime) with velocity, as predicted by Weber, who extended Rayleigh's inviscid analysis to the viscous case. As the jet velocity is increased further, the jet breakup length reaches a maximum and then decreases. A transverse wave disturbance is now observed in addition to the axisymmetric waves. The physical mechanisms causing the peak and the reduction in the intact length of the jet are believed to be the aerodynamic forces in the form of a dynamic pressure and the increase in the level of initial disturbances within and at the exit of the nozzle, see Pinney and Fenn and Middleman.

As the jet velocity is increased further, the flow is now in the turbulent-flow regime and the breakup length is seen to increase again; however, the jet velocity by now is so great that the breakup time, i.e., \( \Delta t \propto \frac{X_b}{V} \), is usually less than that for some laminar velocities. The physical mechanisms involved in the turbulent flow are the greatly increased initial disturbance level near the nozzle exit and the aerodynamic forces which tend to amplify the disturbances, whereas 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 tend to inhibit the growth of the disturbances. More details on these general interpretations may be found in Davies, Townsend, and Pinney.

The case of the flow of a liquid sheet instead of a circular jet has been the subject of research by Dombrowski and Fraser, and Dombrowski and Munday. For the turbulent-flow case, they find that the surface of the sheet becomes very ruffled with cavities and ridges. At high injection velocities aerodynamic waves predominate and the sheet disintegrates. When turbulence is produced at low velocities, i.e., with large orifices, local depressions in the surface will tend to perforate the sheet when they have reached a thin enough region before aerodynamic waves grow to sufficient amplitude.
C. Parameter Effects

The 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 by the use of perturbation techniques carried out for a circular jet—see, for example, Levich (14)—indicate that the jet is unstable for wavelengths greater than \((2\pi r)/(\kappa v^2)\) and that the intact jet length would be approximately thirty times the jet radius. For the present case of a lithium vapor at say, \(p = 0.1\) torr, \(T_e = 2000\) K, \(\rho = 400\) dyne/cm, we calculate that the minimum wavelength for which an unstable jet would result is \(\sim 2(10^4)\) 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 Middleman (8) demonstrate that greater ambient pressure (or density) tends to reduce the intact breakup length. As ambient density is decreased, the intact length increases up to a certain value and remains unchanged. The numerical value for this critical condition below which the ambient effect no longer exists was found by Fenn and Middleman to be: 
\[
(We_{\rho})_{crit} \approx 5.3,
\]
where the ambient Weber number is defined to be 
\[
We_{\rho} = (\rho_{\rho}v^2D)/\rho.
\]
Substitution of appropriate property values in the Weber number yields \(10^{-3}\), much less than 5.3. Thus we again infer that the ambient effect on the present jet (if circular) is negligible.

The "nozzle/fluid" effects. The term "nozzle/fluid" signifies the interactive effects of the liquid-jet fluid property and the nozzle dimension defined to be 
\[
Z = \frac{\mu_j}{r_j}\frac{\rho_jD}{\rho}
\]
and is commonly called the Ohnesorge number. This number, which can also be expressed as a ratio of \(\left(\frac{We_j}{Re_j}\right)^{1/2}\) to \(Re_j\), 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 (6), by Phinney (7,11) and by Lienhard and Day (15) to affect the intact jet length, the critical transition Reynolds number and the initial disturbance level in or near the nozzle. Although the experiments were not performed for the Z value of present interest, i.e. \(Z \approx 10^{-4}\), reasonable extrapolation shows 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 level before breakup. In other words, the convenient parameter \(Q\) first introduced theoretically by Weber (5) can be interpreted to contain only \(X_B/D\) and \(\left(\frac{We_j}{Re_j}\right)^{1/2}\), since 
\[
1 + 3Z \approx 1
\]
in the present case.

The nozzle-configuration effects: By this we mean the influence of the orifice inlet length on the jet-breakup length as observed by Grant and Middleman (6), for the laminar case. Physically there exist different patterns of the velocity profiles of the jet depending upon the nozzle-exit configuration, such as smooth convergent nozzle, an orifice, etc. 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. Additionally the viscosity would affect this transitional behavior at the interface, especially in the turbulent-jet case. To our knowledge this has not been performed for the configuration of present interest. An analysis is currently being made by this writer to determine the extent of its influence on the jet-breakup behavior.
The 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 microexplosion. Should such a phenomenon occur, the duration of such disturbances is estimated to be about 1 ms. 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 possible large initial disturbance levels, encompassing broad range of frequencies, etc. This constitutes another uncertainty in the present turbulent-jet problem. An approximate estimate 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.

For the liquid-mass velocity of 10 m/sec, say, we may express the frequency of the disturbance in terms of wavelength, i.e., \( \lambda = \frac{V}{f} = 10^3 / f \). 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 equation \(^{(14)}\) for the present conditions are \( 10^4 \) 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 Hagerty and Shea \(^{(16)}\) and Dombrowski and Hooper \(^{(17)}\) are used here, recognizing the laminar nature of their analyses. It will be seen later that Phinney \(^{(11,18)}\) claims the existence of some equivalence between the laminar-flow disturbances and the turbulent-flow disturbances, on the basis of correlability of available empirical data. Kusui \(^{(19)}\) also observed the existence of a plateau for the stability parameter \( Q \) for the turbulent-jet flow cases. In any event, application of the stability criteria yields the result that for the sheet flow into the ambient vapor-lithium density of \( 10^{-7} \) gm/cm\(^3\) (corresponding to \( p_0 < 0.1 \) torr) the disturbance frequency introduced at the nozzle should be less than 0.1 cycles/sec, a seemingly unlikely turn of events. We thus conclude that introduction of oscillating disturbances at the nozzle exit will not result in the 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 clearly delineated at the present time.

POSSIBLE EXPERIMENTS AND FUTURE WORK

The "vacuum" effects. The designed ambient condition of the vapor lithium in the reactor chamber at 0.1 torr or less poses a question 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 \(^{(13)}\), 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.

The shape effect. This question is concerned with the different behavior of a circular jet as contrasted 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\(^{(5,6)}\), while for a sheet flow both symmetric and antisymmetric disturbances produce instability of the jet\(^{(16,17)}\). Also, the effect of surface tension in the case of a sheet flow is to bring about shrinkage in the liquid sheet. In the present case of an annular-sheet flow, this may affect the jet-breakup behavior. An analysis and/or experiments in this connection would be helpful.

The vibration/oscillation effect: This particular concern stems from the speculated impingement of shock waves generated by the pellet micro-explosion resulting in a vibrating reactor housing, which in turn would introduce initial disturbances at the nozzle. Although it has been noted earlier that the inferred wavelength may be such that the disturbances are not destabilizing, if circular jet, the conclusion is not reliably established; any contemplated experiments should consider this uncertainty.

The energy absorption effect: Currently it is not known whether the pellet micro-explosion causes the liquid-litium jet to disintegrate or remain intact. It would be very useful if some testing procedure can be found to answer this question. A possibly useful case is the effect of shock waves on a sheet, as in Prien\(^{(20)}\), who found that the reflected shock caused considerably more disruption than the incident shock wave.

Jet-reassembly question: In case the liquid jet is dispersed, we wish to know whether the incoming liquid jet will be discharged into the now highly dispersed reactor chamber and reconstitute itself as a stable, intact jet. Should the effect of energy absorption in the liquid be such that the jet remains undisturbed, this question is a moot one. However, if ever the jet disintegrates, this question takes on a sudden physical significance.

Analysis of the transient flow of a liquid jet can be made and some physical insight might be obtained from the experiments of Bowden and Brunton\(^{(21)}\).

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REFERENCES


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