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Ronald W. Petzoldt

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OSCILLATING LIQUID FLOW ICF REACTOR

Ronald W. Petzoldt

University of California, Lawrence Livermore National Laboratory
P.O. Box 5512
Livermore, CA 94550
(415) 422-9860

ABSTRACT

Oscillating liquid flow in a falling molten salt inertial confinement fusion reactor is predicted to rapidly clear driver beam paths of residual liquid droplets. Oscillating flow will also provide adequate neutron and x-ray protection for the reactor structure with a short (2-m) fall distance permitting an 8 Hz repetition rate. A reactor chamber configuration is presented with specific features to clear the entire heavy-ion beam path of splashed molten salt. The structural components, including the structure between beam ports, are shielded.

INTRODUCTION

As part of the HYLIFE-II reactor studies,¹ we are investigating the use of a falling molten salt composed of fluorine, lithium, and beryllium (called Flibe), for the first wall and blanket of an inertial confinement fusion (ICF) reactor.

The original HYLIFE reactor design² had two driver beams and a repetition rate of 1.5 Hz. The repetition rate was based on a target yield of 1800 MJ (4.5 MJ driver energy times target gain of 400) to produce 1000 MW of electrical power. Even with such a low repetition rate, gravity would not adequately clear the beam paths of splashed liquid from the previous shot before injecting a new target. Less optimistic target gain estimates and higher driver costs may require higher reactor repetition rates. For example, yields of 350 MJ (5 MJ driver energy times target gain of 70) would require the repetition rate to be about 8 Hz, which would not allow time for gravity to clear the beam paths.

We must also ensure that all reactor structural components are shielded from neutron and x-ray damage. This can be accomplished by placing about 0.4 m of molten salt between the structure and the target. High repetition rates require a short fall distance and do not allow for a weir flow to protect liquid nozzles, as in the original HYLIFE design.² The geometry of an oscillating flow can protect structural components and provide access for target and driver beam injection.

CHAMBER AND MOLTEN SALT CONFIGURATION

Flibe is injected down out of nozzle pipes into the reactor chamber (Fig. 1). Rotating cams and flywheels drive the motion of the oscillating pipes. Ion beams enter the cavity formed by the oscillating Flibe and strike the injected target. Some of the pipes are stationary, others move horizontally to

impart an oscillating motion to the Flibe. For clarity some of the details were left out of Fig. 1. For example, the required pivot pins and bearings shown in Figs. 7 and 8 are not shown here. Volumetric flow rate of the Flibe is about 60 m³/s with a ratio of Flibe to empty space of 0.67 at the nozzles.

The reactor chamber wall and the structural housing that encloses the ion beam path and directs Flibe from the path are shown in Fig. 2. The housing protrudes 1.2 m into the reactor chamber. Within the housing, a vertical clearing plate moves horizontally across the beam path to clear residual Flibe droplets. The neutron shield protects the ion beam focusing magnets.

Rotating flywheels attached by drive rods to the piping that extends through the reactor chamber cause the sinusoidal oscillation of the pipes (Fig. 3). Bellows seal the vacuum inside the chamber. The nozzle motion imparts a horizontal motion to Flibe exiting the piping.

Fig. 1. Oscillating flow HYLIFE II reactor chamber. Flibe from the oscillating pipes forms a cavity in which the microexplosion takes place and results in an opening for the beams to propagate to the target.

Fig. 2. Cross section of the reactor chamber at target elevation showing oscillating and nonoscillating Filibe. (horizontal slice of Fig. 1)

According to calculations using basic kinematics,³ the instantaneous position of the Filibe (0.005 s before the closest approach of the nozzles) would be as shown in Fig. 3. The Filibe forms a cavity into which the target is injected. At the time of fusion, the minimum standoff distance from the target to the liquid wall is about 0.5 m. (The Filibe position and shape shown below the dashed line is not based on calculations.)

The fusion shot microexplosion will cause an outward motion (on the order of a few meters per second) and chaotic splashing of the Filibe superimposed on the existing Filibe motion (which is mostly downward at about 16 m/s).

The two most important benefits of oscillating flow are the clearing of splash to provide open target and beam paths and the shielding of nozzles with short fall distances to allow high repetition rates. The Filibe moving down from above, including that in the piping when the previous shot occurred, sweeps a volume clear. Follow-on Filibe oscillates out of the target and beam paths. Additional Filibe closes in above the paths to provide shielding for the nozzles. Although further analysis is needed, adequate shielding should be provided by fall heights of about 2 m. With a Filibe injection velocity of 16 m/s, a repetition rate of 8 Hz is obtained.

Driver Beam Path Formation and Clearing

Ion beams penetrate the beam shield and reactor chamber wall 3 m from the chamber center to converge on the target (Fig. 4). The structure between the ion beam holes is shielded from neutrons and x-rays by 0.4-m-thick horizontal

Fig. 3. Reactor chamber showing the primary oscillating flows (vertical slice of Fig. 1 at 0 m).

jets about 2.8 m from the center of the chamber. The Filibe flows from the nozzles, between the ion beams, and into the receiver.

The structural beam housing (1.8 to 3.0 m off center) directs Filibe remaining from the previous shot away from the beam path, as shown in Fig. 2. The clearing plate oscillates within the housing to clear the beam and target paths of any remaining Filibe droplets.

Fig. 4. Beams pass through penetrations in the shield and reactor vessel. Horizontal jets shield beam ports from x-rays and neutrons.

Filbe is shown in Fig. 5 at various locations (see scale on Fig. 2) just before the fusion shot. At 1.5 m from the center, the oscillating flow arrangement restricts neutrons and x-rays to a short narrow path, thus shielding the structure behind the Filbe. There is no exposed structural surface within about 10 m. Because the beams are converging, the beam height is shorter at 1.0 m off center than at 1.5 m, and shorter still at 0.6 m. The target, in a vacuum at the reactor center, is surrounded by the Filbe about 0.5 m from the target.

Target Injection

Targets could be injected through the same path followed later by the beam, perhaps through the center beam port. The clearing for the beam path subtends an angle of 25° (Fig. 6). As the target passes horizontally through the beam path formed by the vertically flowing Filbe, the lower edge of the path slopes 12.5° from horizontal. The target velocity must be high enough to reach the center of the reactor chamber before the Filbe surrounding the beam path falls past the target elevation. The relative motion of the target through the

Fig. 5. Filbe at various distances from the reactor center immediately preceding the fusion shot (a) 1.5 m, (b) 1 m, (c) 0.6 m, and (d) on centerline. These distances can be seen using the scale shown in Fig. 2.

Fig. 6. Target velocity geometry and calculation.

Filbe opening is such that the target is injected along the lower edge of the Filbe opening.

This work is based on a repetition rate of 8 Hz and a flow velocity of 16 m/s, giving a 2-m fall height between shots. Lower repetition rates can be accommodated by decreasing the flow velocity and increasing the fall height.

DESIGN OF MOVING COMPONENTS

Main Oscillating Flow Components

To obtain the desired flow trajectory, some of the nozzles must oscillate. The required oscillation of the main nozzles is 10.10 m. In the base case arrangement (Figs. 3 and 7) nozzles are driven from outside the reactor chamber by a flywheel-linkage arrangement, the vacuum at the top is maintained by a bellows seal, and the piping is stiff to minimize flexing as it is driven back and forth by the flywheel.

A significant amount of piping outside the reactor chamber must oscillate. The piping is fabricated in a U-shape to minimize twisting; the oscillations are driven from both sides of the U.

There must be a point of flexure in the pipe below the bearings on the right side of Fig. 7. Two possible means of providing this flexure are to install either a bellows or a carbon fiber fabric in the pipe. The fabric connection would require a leak-collection chamber welded to the Filbe piping as well as a bellows seal at the upper edge.

A cross-section at the pivot-pin elevation is shown in Fig. 8. The right side is upstream of the left side; the reactor chamber is directly below the left-side flow channels. Two pivot pins and two Filbe pipes are connected to each support structure. The horizontal forces exerted by the pins on the support structure are in opposite directions, therefore the net horizontal force on the structures is nearly zero.

Two alternative approaches to the base case that have been considered and may have merit involve driving the nozzles from inside the reactor chamber (Fig. 9). A bellows provides a seal around the drive rod because the Filbe environment does not permit a standard lubricated seal.

The first approach has no pivot joints in the piping and would require significant flexing of the steel pipes. To reduce the strain involved with the flexing, the nozzle pipe could be composed of many rectangular tubes tied together at the top and bottom (Fig. 10).

Fig. 7. Side view of an oscillating pipe (rotated 90° from Fig. 2).

Fig. 8. Bearings and flow channels (plan view).

Fig. 9. Reactor and primary oscillating Fibre flow.

The drive rod can be attached to the nozzles by a hinged joint if adequate lubrication and cooling are provided. Without a hinged joint, the drive rod will have to be very rigid to prevent buckling. The tubes would be held rigidly at the top, as shown. Without a hinged joint, the tubes would remain vertical at the bottom and motion would cause the tubes to oscillate from a straight to a flexed position (Fig. 11). The problem with this approach is fatigue life of the tubes. To reduce strain in the tube and provide a fatigue life of 30 y, very long tubes with very small widths are required (e.g., 12 m long for a 4-cm-wide flow channel).

Long narrow Fibre pipes with high flow velocities have high pumping power requirements.

The second internally driven approach, uses a pivoting Fibre nozzle concept to reduce the strain and fatigue on the nozzle tubes, as shown in Fig. 12. The reactor chamber is sealed from the atmosphere by a bellows. The bending of the pipe is accomplished in the bellows above the pivot pin. An advantage of the internally driven arrangements is that only the Fibre piping inside the reactor chamber must oscillate.

Beam Path Flow Components

The nozzle piping that provides the beam path flow will be similar to but smaller than the main oscillating pipes. The nonsinusoidal pipe motion could be driven by a rotating

Fig. 10. Separated nozzle piping.

cam. The motion of the nozzle is derived³ and the general shape of the cam required to approach the desired trajectory of the Fibre for the beam path as shown in Fig. 6 is calculated in Ref. 3.

A constant velocity vertical nozzle produces a vertical Fibre profile. To understand this it may help to consider the reference frame in which the nozzle is at rest. An accelerated nozzle produces a curved Fibre profile. The nozzle need not move as far horizontally as the width of the beam path. The "sharpness" of the ends of the beam path is directly proportional to the acceleration that can be provided to the nozzle.

FORCES AND POWER REQUIREMENTS

For a repetition rate of 8 Hz, the maximum force required³ to be exerted on the base case main oscillating flow nozzle piping is about 1.2×10^6 N.

Most of the energy provided to the nozzle pipes to accelerate the pipes full of Fibre is returned to the flywheel as the Fibre pipes are decelerated. The energy required to provide the horizontal motion of the Fibre that leaves the nozzle is not returned. The power provided to the motors to cause oscillation of the Fibre is about 2.7×10^5 W.

The required radius of a flywheel for the main nozzle piping is about 0.6 m with a thickness of 0.15 m.

REMAINING CONCERNS

There are several concerns regarding this concept that remain to be investigated:

1. Although very long life has been achieved in bellows applications (e.g., air pumps) the lifetime may be degraded

Fig. 11. Filbe tube deflections (relative magnitude of tube bending is exaggerated).

Fig. 12. Internally driven pivoted Filbe nozzle.

at elevated temperatures in a Filbe and neutron environment. If possible, a bellows should be designed with adequate convolutions to have a dynamic fatigue lifetime of 30 y. A suitable test program should be conducted in a Filbe environment to ensure adequate bellows life.

2. Dynamic stress analysis of the chamber walls and internal structure is made difficult by asymmetric flow geometry—stress concentrations may occur.
3. Adequate neutron shielding of nozzles and some reactor structure has not been verified.
4. Effect of fusion blast on Filbe velocity in this flow geometry has not yet been adequately investigated.
5. No adequate flexible joint for Filbe piping has been designed.
6. Although the oscillating Filbe should sweep the beam paths clear of Filbe left from previous shots, it has not been proven that the beam paths will be adequately cleared.

Summary

Oscillating flow permits a high-repetition-rate liquid-wall ICF reactor. Oscillating flow can provide clearing and subsequent reopening of the beam and target entry paths for an enclosed cavity in which the fusion blast may be contained. A combination of vertical and horizontal Filbe flows can shield the reactor structure around beam and target entry holes as well as the nozzles. A disadvantage of this concept is the requirement for moving parts in the reactor chamber.

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