UCRL-91590

PREPRINT

CONF-850316--88

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This paper was prepared for submittal to
6th ANS Topical Meeting on Technology of
Fusion Energy, San Francisco, CA
March 3-7, 1985.

April 15, 1985

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FLOW CHARACTERISTICS OF THE CASCADE
GRANULAR BLANKET*

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ABSTRACT

Analysis of a single granule on a rotating cone shows that for the 35° half-angle, double-cone-shaped Cascade chamber, blanket granules will stay against the chamber wall if the rotational speed is 50 rpm or greater. The granules move axially down the wall with a slight (5-mm or less) sinusoidal oscillation in the circumferential direction.

Granule chute-flow experiments confirm that two-layered flow can be obtained when the chute is inclined slightly above the granular material angle of repose. The top surface layer is thin and fast moving (supercritical flow). A thick bottom layer moves more slowly (subcritical flow controlled at the exit) with a velocity that increases with distance from the bottom of the chute. This is a desirable velocity profile because in the Cascade chamber about one-third of the fusion energy is deposited in the form of x rays and fusion-fuel-pellet debris in the top surface (inner-radius) layer.

INTRODUCTION

The Cascade concept^{1,2} for an inertial-confinement-fusion reactor (see Fig. 1) includes a rotating double-cone-shaped chamber where a moving, 1-m-thick, ceramic granular blanket is held against the reactor wall by centrifugal force. The granules absorb energy from fusion reactions occurring in the center of the chamber. The inner 10 cm of the blanket is composed of BeO granules and the outer 90 cm is composed of LiAlO₂ granules. All granules are approximately 1 mm in diameter - about the size of sand grains. Approximately one-third of the fusion energy is deposited at the inner surface of the

blanket in the form of x rays and fusion-fuel-pellet debris. The remainder of the fusion energy is in the form of neutrons which are absorbed in the balance of the blanket.

Neutron-energy absorption has an approximate exponential form (larger at the inner surface) in both the BeO and the LiAlO₂ but there is a step increase of about a factor of two at the interface when passing from the BeO to the LiAlO₂. Overall, there is an order of magnitude more neutron energy deposition occurring at the inner surface than at the outer surface.

We desire a radial velocity gradient in the blanket that matches the energy absorption in the BeO and LiAlO₂ regions so that the blanket exit temperature is as spatially uniform as possible. This allows the highest average exit temperature and the highest potential efficiency for conversion of heat into electricity.

As part of our investigation of granular-flow behavior in the Cascade chamber, we analyzed the motion of a single granule on a rotating cone. We found that individual granules will stay against the chamber wall as long as the rotational speed is 50 rpm or greater. This produces the desired open space in the center of the chamber that must be present for fusion-fuel-pellet injection and laser (or ion) beam propagation used to illuminate and compress the pellets to fusion conditions. From the calculations of individual granule motion on the cone surface, we infer the motion of granules present within the blanket and show that their motion relative to the chamber wall is generally axial but with a slight (5 mm or less) sinusoidal motion in the circumferential direction. The sinusoidal motion results from the changing direction of gravity as the chamber rotates.

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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Cascade: A rotating ceramic-granule-blanket reactor

Fig. 1. Rendering of the Cascade reactor.

We also report experimental results for sand flowing down a chute, and we demonstrate that with appropriate design of the exit region, a natural two-layered flow can be induced when the free surface is slightly above the angle of repose of the sand. In this two-layered flow a thin, top-surface layer moves at supercritical speed. In the Cascade reactor, this thin, fast moving (inner-radius) layer absorbs all of the x-ray energy and fusion-fuel-pellet debris energy, with most of the neutron energy passing through to the thick outer-radius layer of the blanket. Significant mixing occurs in this thin, inner-radius layer which results in a nearly uniform exit temperature in the layer.

The thick bottom layer moves more slowly (subcritical flow controlled at the exit). Laboratory scale experiments show a velocity profile in the thick, bottom layer with as much as an order of magnitude higher velocities occurring in the upper region than along the bottom wall. In Cascade, this profile helps to produce a more uniform exit temperature in the outer-radius layer of the blanket.

MOTION OF A SINGLE GRANULE ON A ROTATING CONE

On the inner surface of a rotating cone, frictional, gravity and Coriolis forces acting on a granule are not always colinear.³ These forces can be divided into two orthogonal components: one purely

circumferential and the other in the direction of a projection of the cone axis on the surface. We call the latter the axial-surface direction. The Coriolis force always acts in a purely circumferential direction with its magnitude depending on the rate of change of the radius (i.e. on the axial-surface velocity). The component of gravity acting in the axial-surface direction is constant - independent of position and/or velocity of the granule. The component of gravity in the circumferential direction varies sinusoidally with time as the cone rotates. The maximum magnitude of the friction force depends on the normal force and on the coefficient of friction; the direction of the friction force depends on the direction of the surface velocity (because friction acts to oppose sliding motion).⁴ In our numerical integration of the equations of motion for a single granule we used the following expressions for the three components of the granule's acceleration in the normal, circumferential and axial surface directions when it was sliding on the cone's surface:

$$a_n = \left[\left(\frac{v_\theta}{r} + \omega \right)^2 r + g \cos(\omega t + \theta) \right] \cos \alpha \quad (1)$$

$$a_\theta = -2 \left(\frac{v_\theta}{r} + \omega \right) v_a \sin \alpha - g \sin(\omega t + \theta) - \mu a_n \left(\frac{v_\theta}{|v_t|} \right) \quad (2)$$

$$a_a = \left[\left(\frac{v_\theta}{r} + \omega \right)^2 r + g \cos(\omega t + \theta) \right] \sin \alpha - \mu a_n \left(\frac{v_a}{|v_t|} \right) \quad (3)$$

Here ω is the rotational speed of the cone, t is time, θ is the angle of the granule relative to its starting position, r is the cone radius at the current position of the granule, v_θ is the circumferential velocity of the granule relative to a point at the same radius rotating with the cone, v_a is the axial surface velocity of the granule on the cone surface, α is the cone half angle, g is the acceleration of gravity, μ is the effective coefficient of friction between the granule and the wall, and

$$v_t = \sqrt{v_\theta^2 + v_a^2}$$

is the total tangential (surface) velocity.

The first term on the right hand side of each equation is associated with centrifugal force or, in Eq. 2, with the Coriolis force. The second term accounts for gravity forces. The last term in Eqs. 2 and 3 is due to the frictional force that acts to decelerate a moving granule.⁴ The normal-direction acceleration, a_n , is opposed by the cone surface so no net motion occurs in this direction.

We numerically integrated Eqs. 2 and 3 to obtain the displacement time history of individual granules for a variety of rotational speeds, effective coefficients of friction and cone half angles. Initially we assumed that the actual inner surface of a granular blanket would be a cone with a half angle equal to the angle of repose for the material (and independent of the shape for the outer chamber wall), and that μ was equal to the tangent of the angle of repose. We determined the minimum rotational speed required to keep a granule in continuous contact with the cone surface. In these calculations, $\tan \alpha$ was set equal to μ , and the granule was initially moving with the cone at the bottom of a 1-m-radius inlet region. We found that the minimum rotational speed was about 50 rpm for $24^\circ < \alpha < 35^\circ$. We also found that in all these cases the calculated axial motion of the granule involved considerable acceleration, and the resulting residence time was significantly less than what we would infer from our granule chute-flow experiments. Additional calculations with the cone half angle a few degrees less than $\tan^{-1} \mu$, showed that the granules then moved only a short distance down the rotating cone before coming to rest on the cone surface. We interpret this result as indicating that the actual inner surface of the flowing granular layer will be at a cone half angle whose tangent is slightly less than the effective coefficient of surface friction (i.e., the angle of repose).

To determine the probable shape of the inner-radius layer surface, we reasoned that a frictional granule would not accelerate in an unlimited manner on a surface whose "effective slope" includes the effects of all forces acting on the granule. With a fixed $\mu = \tan 35^\circ$, we examined various cone surface angles to see under what circumstances a granule would undergo unlimited acceleration, would come to rest, or would lose contact with the wall.

For each assumed inner-surface half angle we obtained a different minimum rotational speed to maintain continuous contact with the wall (for a cone with an initial radius of one meter). The values varied from the cylindrical value of near 37 rpm for a zero half angle to 50 rpm when the cone half angle became equal to the arctangent of the assumed coefficient of friction. However, reduction of the cone half angle by only a few degrees below the value corresponding to $\tan^{-1} \mu$ eliminated the unrealistic, unlimited acceleration discussed above. At rotational speeds above 45 rpm all sliding relative to the cone surface ceased after the first meter or so of length down the cone. This implies that the inner-surface half angle will probably be very close to the angle of repose for the material except for perhaps a small region near the inlet of the chamber where the inner-surface half angle would be a few degrees smaller than the angle of repose.

We also considered the motion of a single granule simulating the movement of the entire blanket in a Cascade chamber. To do this we added a constraint to the maximum axial velocity of the granule that corresponds to the total expected mass-flow rate of granules through the chamber, assuming a constant-thickness granular blanket. With this restriction on v_a , we examined the motion of a granule with $\mu = \tan 24^\circ$ on a 35° cone with an initial radius of 2.0 m, corresponding to a granule in contact with the chamber wall near the inlet region. We looked at rotational speeds from 40 to 50 rpm and found that such a granule moved steadily down the cone according to the constraint condition, coupled with very small, almost sinusoidal, circumferential oscillations in its trajectory. The amplitude of these oscillations varied from ± 1.5 cm at 40 rpm down to less than ± 0.5 centimeters at 50 rpm. These calculations indicate that circumferential oscillations of the flowing granular layer, if they occur at all in a full-size Cascade chamber, will be very small and will have only a negligible effect on the granular blanket thickness at the top of the chamber.

GRANULE CHUTE-FLOW EXPERIMENTS

We conducted a series of experiments with the inclined rectangular chute shown in Fig. 2 to determine the flow characteristics of the Cascade granular blanket. These experiments, combined with the analysis discussed above, were used to establish the 35° half angle of the Cascade double-cone-shaped chamber. From

r experiments, we infer that a two-layer, moving granular blanket in Cascade is feasible. The inner-radius layer is thin, has high speed, and has almost complete mixing. The thick, outer-radius layer of the blanket moves more slowly with a velocity controlled at the exit. The velocity profile in the outer-radius layer decreases with radius.

Fig. 2. Test apparatus for the granule chute flow experiments.

The chute shown in Fig. 2, is 250 mm wide, is made of clear plastic, and was inclined at angles around 35° . Monterey crystal amber-colored sand, Type O, was used in the experiments. This sand has an angle of repose of about 34° and a grain size of about

0.5 mm. However, we noted that the slope of the sand on the chute during experiments was closer to 32° , indicating dynamic conditions may lower the effective angle of repose.

Experiments were conducted by filling the upper container (positioned on a fork lift in Fig. 2) with sand. The upper container was placed so that a pipe extending from the bottom of the container ended in an inlet hopper that led to the entrance of the inclined chute. When a plate in the bottom of the upper container was opened, sand would fill the inlet hopper to the elevation of the pipe exit. As sand moved out of a weir at the bottom of hopper and down the chute, replacement sand from the upper container would automatically refill the hopper.

Sand was prevented from flowing out of the chute until the start of a test by positioning a removable plastic barrier just upstream of the bottom end of the chute. When the plastic barrier was removed, sand would flow to the bottom end, out one or more of five exit weirs and into a second container (see also Fig. 3). The second container was located on a scale so we could determine the flowrate. We adjusted the flowrate out of the various weirs by changing the angle of individual weir exit plates. If an individual weir exit plate were close to horizontal, then no sand would flow out of that particular exit weir. We conducted tests with the middle three weirs closed - with flow only out of the top and bottom weirs. With the middle weirs closed, a thin, fast moving layer developed on the chute. Sand in this layer and slight below was removed by the top weir. The rest of the sand was removed by the bottom weir. We did not close the bottom weir because this would establish a zone upstream where the sand was stationary. If stationary granules were present in the Cascade blanket, the granules would continue to heat up until they melted, thereby destroying the granular nature of the blanket. The middle three weirs were not used: tests with various weirs open showed that using the bottom weir only was more effective and produced similar results. In later tests, we used two exit containers and two scales so we could establish independent flowrates from the top and bottom weirs.

The sand was seeded with a small amount of white-colored alumina which had a lower density and an average grain size larger than the sand (~ 3 mm). The alumina granules remained on the top layer of sand as it flowed down the chute, and acted as markers for motion pictures. We positioned flat mirrors at an angle so that when viewed from the side, the top surface, side, and bottom surface could be seen simultaneously with a motion picture camera (Fig. 3).

Fig. 3. Time exposure of two-layered flow on a chute inclined at 36.6° . Vertical markers are 2 cm apart and horizontal markers are 10 cm apart.

In the above tests, data consisted of geometrical measurements to establish the chute inclination, sand flowrates, and motion pictures taken at 50 frames/s. By viewing the motion pictures frame by frame, we determined the velocity of the sand as a function of distance from the bottom of the chute. In some cases we took time-exposure photographs, an example of which is shown in Fig. 3. Here the chute is inclined at a 36.6° angle and the bottom weirs are closed to prevent motion in the bottom layer. The sand entered the chute from the weir at the bottom of the inlet hopper. Sand at the upper right of the chute (shown in Fig. 3) is flowing down at supercritical speed. Because of the time exposure of the photography, the sand is seen as a blur rather than individual sand grains. In the center of the photograph, the flow changes abruptly with only a thin layer at the top flowing at supercritical speed down the chute and out the top exit weir. The bottom sand layer is stationary and individual sand grains can be seen. No flow was permitted out the bottom four exit weirs for this particular test. The central transition region is similar to a hydraulic jump with liquid flow. Note that the top mirror shows rapid flow over

the entire width of the chute. The bottom mirror shows stationary sand separated from moving sand by a curved line.

When the bottom as well as the top exit weir was opened, the desired two-layered flow was obtained. The region of stationary sand then flowed at subcritical speed; the boundary between subcritical flow and supercritical flow seen on the bottom mirror moved upstream and the curvature of the boundary was substantially reduced. The effects of the sides of the chute were still present but were smaller. Furthermore, the depth of sand in the region where there was a thin supercritical top layer flowing over a thick subcritical flow layer was nearly uniform rather than increasing to the lower left in Fig. 3.

The boundary between two-layered flow and complete supercritical flow moves even further upstream if the incline of the chute is reduced to a value closer to the sand's angle of repose. A small region of complete supercritical flow is always present just downstream of the weir in the bottom of the inlet hopper, but it is only a few centimeters

long when the inclination angle is between 35° and 36° .

Figure 4 shows the velocity profile when two layered (supercritical/subcritical) flow exists on a chute inclined to 36° . These data were obtained from motion pictures, taken at 50 frames/s, in which individual grains of sand on the side of the chute were followed from frame to frame. Total flowrate was measured by weighing the amount of sand flowing into the exit container over a period of ~ 30 s and dividing the mass flow rate by the bulk density of the sand. The flow rate so measured was $940 \text{ cm}^3/\text{s}$ and the flow rate calculated by integrating the velocity profile was about 20% lower. The two values are in reasonable agreement and give confidence in the accuracy of both flowrate and velocity measurements. Further, the integrated flowrate is less, which is expected when edge effects are considered.

Fig. 4. Velocity profile of two-layered flow down a chute inclined at 36° . The entrance weir is 4 cm high.

Data reduction of tests where flowrate in both layers was measured individually has yet to be completed.

CONCLUSIONS

Analysis of the motion of a single granule on a rotating cone shows that the blanket granules will be held against the Cascade chamber wall if the rotational speed is 50 rpm or greater. This results in a clear, open central region into which fusion-fuel pellets can be injected and illuminated by laser (or ion) beams that compress the fuel pellets to fusion conditions. Motion of granules inside the blanket is essentially axial with small (less than 0.5 cm) sinusoidal oscillations in

the circumferential direction. Further, the blanket inner-radius surface will have a half-angle close to the angle of repose of the granular material.

Experiments showed that two-layered granular flow can be obtained on a chute, inclined slightly above the angle of repose. The top layer is thin and moves with high speed (supercritical flow). The thick bottom layer moves more slowly, with the velocity controlled at the exit of the chute. The velocity distribution in the bottom layer decreases with distance below the top surface. This two-layered flow is advantageous for Cascade because about one-third of the fusion energy is deposited in the thin, fast-moving inner-radius surface layer of the blanket. The fast speed permits a reasonable change in temperature as the granules pass through the blanket. The velocity distribution determined from these tests allows design of a thermally efficient blanket for the Cascade chamber.

REFERENCES

1. J. H. PITTS, "Cascade: A Centrifugal-Action Solid-Breeder Reaction Chamber," *Nuclear Technology/Fusion*, 4, 96/ (1983).
2. J. H. PITTS, "Development of the Cascade Inertial-Confinement-Fusion Reactor," 6th Topical Meeting on the Technology of Fusion Energy, San Francisco, CA, March 3-7, 1985. Available as Lawrence Livermore National Laboratory Report UCRL 91589.
3. J. H. PITTS and O. R. WALTON, "Granular Flow Along the Interior Surface of Rotating Cones," 8th International CHISA Meeting, Prague, Czechoslovakia, Sept. 3-7, 1984. Available as Lawrence Livermore National Laboratory Report UCRL 90742.
4. J. T. ODEN and J. A. C. MARLINS, "Models and Computational Methods for Dynamic Friction Phenomena" to appear in *Computer Methods in Applied Mechanics and Engineering*, North Holland, Amsterdam.