Free Convection Liquid Metal Target

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As an alternative to the present forced convection liquid lead-bismuth (LBE) target concept, the possibility of a sealed LBE target has been looked into as was mentioned in the survey talk. The target consists essentially of a cylindrical vessel of about 4 to 6 m length and a diameter of 20 to 25 cm filled with LBE (see Fig. 1). It is centered on the axis of the proton beam which enters the target through a conical graphite window at the lower face of the target vessel. In the upper half of the vessel, a cylindrical array of cooling pipes near the wall of the vessel serves as a heat exchanger. In order to guide the resulting free convection flow of the LBE, especially at start-up, a concentrical tube is inserted which separates the upward and downward LBE streams.

In order to study the feasibility of such a source concept, the characteristics of the stationary flow can be obtained by assuming an uniform turbulent flow pattern (Kolbenströmung) where the buoyancy of the hot LBE is balanced by the frictional flow forces on the flow surfaces and in particular on the cooling pipes and the resulting pressure drop Δp is quadratically dependent on the flow rate $\dot{V}$ =

$$\Delta p = k \cdot \dot{V}^2$$

Energy balance between buoyancy and friction yields

$$\frac{dE_b}{dt} = \frac{dE_f}{dt}$$

$$h \cdot g \; \frac{d(\rho V)}{dt} = \Delta p \cdot \dot{V}$$

$$hg \; \rho \beta T_\infty \; \dot{V} = K \dot{V}^3$$

where h = mean vertical rise of hot LBE

ρ = mean density of LBE

β = thermal volume expansion coefficient of LBE

g = acceleration of gravity

T_∞ = temperature difference between hot and cold LBE stream

The problem is simplified by the fact that the heating power P is deposited independent of the flow pattern:

$$P = c_p \; \dot{V} \; T_\infty$$

we therefore find

$$T_\infty = \left[\frac{kP^2}{h} \Big/ \left(c_p^{\,2} \rho g \beta \right) \right]^{1/3}$$

$$\dot{V} = \left[\left(\frac{Ph}{k} \right) \cdot \left(\frac{\rho g \beta}{c_p} \right) \right]^{1/3}$$

For a beam power P of 1 MW, a reasonable friction factor k of $3\cdot 10^{-3}$ bar $/(l/s)^2$ and a rise h of 2 m we obtain a temperature rise of 200 °C and a flow rate $\dot{V}$ of about 3,6 l/s which is comparable to the assumed values for the forced convection case. As the expressions for T_∞ and $\dot{V}$ show, beam profile and stopping distribution do not enter the overall flow characteristics but only influence local convection currents near the stopping region.

As further important aspect of free convection flows is the start-up phase. The flow element closest to the beam entrance window is overheated the most because it takes longest to move out of the beam heating region. To calculate the temperature rise in this element we can neglect frictional forces compared to inertial forces in the flow. If as a further approximation the heating is assumed to be uniform over a finite length of the inner tube of the target vessel, then the temperature rise ΔT_{max} of the critical flow element and it is velocity w when leaving the heating zone can be calculated analytically,

$$\Delta T_{max} = \left(\frac{Q^2 L}{\gamma} \cdot \frac{6}{c_p^2\, g\beta}\right)^{1/3}$$

$$w = 3\cdot l \left(\frac{Q\gamma}{L} \cdot \frac{g\beta}{6\, c_p}\right)^{1/3}$$

where Q is the heating power density, γ the sine of the angle ε

of inclination of the target axis, L the total length of the average flow path in the target, and l the length of the heating zone.

For a vertical target (γ=1) of an inner diameter of 16 cm and a length of 3 m (L=600 cm). ΔT_{max} is about 1200 °C and w=10 cm/s or about half the stationary velocity. Distribution of the heating power over the cross section of the inner tube is effected by local convection currents. Local overheating is to be expected but estimates show that due to the large latent heat of evaporation vapor bubble formation is quite unlikely. More detailed calculations of the time dependent convective flow are in progress.

From the technical point of view a free convection target described above would eliminate the need for a LBE circuit. In case of a target change, only the secondary cooling circuit whose activation is minimal would have to be disconnected and the highly radioactive LBE would remain sealed in the target container. Although somewhat larger than the forced convection target, the free convection target is a relatively inexpensive unit which could be discarded if it failed thus eliminating the need for expensive hot-cell repairs. A disadvantage is the relatively large amount of LBE (150 to 200 l) which would escape into the containment in case of a window failure. A drainage pipe would have to be connected to the proton beam vacuum pipe which would collect and slow down the leaking LBE and feed it into a shielded dump. Preheating and melting of the LBE content of the target at start-up could be achieved by circulating hot gas through the last part of the beam vacuum pipe.

A particularly attractive neutron source concept is the combination of a vertical free convection target incorporated in a vertical beam source allowing thermal neutron ports distribution over the full circumference of the source as described in the summary table. A more detailed technical study on this version is in progress.

Fig 1: Free Convection LBE Target