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THE LIQUID METAL TARGET FOR THE GERMAN NEUTRON SOURCE (SNQ) - STATUS OF THE THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF THE TARGET THERMO- AND FLUIDDYNAMICS -

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ABSTRACT

The heat released in the target of the SNQ amounts to several MW and must be transfered continuously to a heat sink. Flowing liquid metals (PbBi, Pb) can be used as target material as well as for heat transport. The liquid metal target can be realized as standing vertical cylinder or as lying horizontal plate type design:

- A funnel shaped hollow jet coalesces to a free falling cylinder jet forming the target. At the location of coalescence the proton beam injects vertical the free liquid target surface.
- In a curved channel of rectangular cross section a plate type target with a nearly vertical free surface is formed by centrifugal forces acting on the flowing liquid metal. The proton beam hits horizontal the free liquid target surface.

Theoretical and experimental investigations of the global flow behavior, the velocity and temperature distributions show that a standing cylinder target can be realized. A stable free jet with only small local flow reductions near the point of coalescence could be demonstrated in H_2O- and PbBi-flow supporting a developed hollow jet theory. Two PbBi circuits are operable to study the handling of PbBi and for investigations of model and true scale test section geometries. For the horizontal curved rectangular channel target up to now only theoretical calculations have been performed. Results already proved heat removal being possible in temperature levels clearly lower than limiting values. Experiments were prepared to demonstrate the operability of this target design and to proof the flow behavior.

THE LIQUID METAL TARGET FOR THE GERMAN NEUTRON SOURCE (SNQ) - STATUS OF THE THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF THE TARGET THERMO- AND FLUIDDYNAMICS -

1. INTRODUCTION

A liquid metal target for the spallation neutron source (SNQ) is being investigated as an alternative to the rotating wheel /1/. The flowing liquid metal is so routed that optionally a vertical cylindrical or a horizontal plate shaped target geometry is obtained. The cylindrical target geometry calls for a vertical, the plate type geometry for a horizontal entrance of the proton beam. Whilst the cylindrical target version requires a specific station, the plate shaped target can be mounted on the support to be provided for the wheel target design. Both versions could then be installed and interchanged at option.

The objective of the investigations was to prove that a liquid metal target with free surface of the flowing target material (Pb, PbBi) seems to be feasible in the desired geometries. The target is to fulfil the following requirements:

- Stable flow passage with free surface, implying that at the point where the proton beam hits the target, a fixed window as a flow guidance can be dispensed with.
- Safe heat removal. At the point of maximum load the lowest possible temperature shall prevail. Any excessive temperatures occurring shall appear within the fluid and not at the confining walls so as to minimize the influence on material properties undergoing variations due to corrosion and neutrons.
- Confinement of the volatile radioactive spallation products. Since the release of radioactive products into the evacuated space of the accelerator becomes the smaller the lower the temperature of the releasing surface is, the free surface should have the inlet temperature.
- Control of the material problems. The main aspect to be considered is the change of material properties due to protons and neutrons. However, these problems must be solved for both the rotating wheel and the liquid metal target.

Two target versions complying with these requirements have been described in /2/. These are (Fig. 1):

- The cylindrical target: In a funnel-shaped nozzle the target material flows vertical downward as a liquid film. After leaving the nozzle the hollow jet coalesces to a free falling full cylindrical jet (point of coalescence) mainly by the effect of the forces of gravitation and surface tension. The proton beam hits the target surface vertically at the point of coalescence.
- The plate target: In a curved rectangular channel the liquid target material is pressed agains the outer curvature of the bended channel by the effect of centrifugal forces. At proper design of the channel the

fluid separates from the inner bend of the channel forming a free surface for the horizontally injected proton beam.

Both versions are suited for removing very high thermal powers. Compared with the operational data indicated in /2/ we have reduced:

- the thermal power to be removed from 4.2 to 2.8 MW in order to have values comparable with that of the rotating wheel /1/;
- the overall temperature level by 125 °C for the PbBi target, allowing a reduction of the inlet temperature from the previous value of 325 °C to 200 °C, implying that the release of radioactive materials for the proposed vacuum of 10^{-3} torr could be reduced by the factor 10^3 just above the liquid metal surface /3/.

The following operating parameters form the basis of the design:

- proton beam intensity	(E)	1100	MeV
current	(I)	5	mA
power	(Q)	2.8	MW
penetration	(R)	60	cm
- mean target diameter		10	cm
- PbBi temperature, target entrance		200	°C
- PbBi velocity (averaged)		3	m/s
- vacuum above free surface		10^{-3}	torr

With these data the flow passage through the target and the heat removal were investigated. The global values so calculated have also been entered in Fig. 1. The following statements relate to the determination of local values and shall prove that flow passage through the target does not bring about local temperatures which could adversely affect the safe removal of the heat.

2. THERMO- AND FLUIDDYNAMIC STUDIES OF THE VERTICAL CYLINDRICAL TARGET

2.1 Thermodynamic Computation

Consideration of the local temperature conditions in the target requires knowledge of the heat source distribution within the target. For the axial and radial power distributions the relationships given in /1/ are used. For 1.1 GeV proton intensity and 60 cm depth of penetration we obtain:

axial power distribution: $H(z) = 214 \cdot \exp(-\Sigma \cdot z)$ kW/cm
radial power distribution: $\phi(r,z) = (H(z)/\pi \cdot s^2) \cdot \exp(-r/s)^2$ kW/cm³

where Σ = macroscopic inelastic cross section
z = distance from beginning of target
r = radius of proton beam (assumed value $r = 5$ cm)
s = variance ($s = r/2$)

If one uses the assumption made above on the flow condition and power distribution, the temperatures of the target in the axial and radial directions can be assessed for the following conditions:

- slug flow,
- only thermal conduction taken into account,
- constant material properties.

The results are indicated only for steady-state power operation. Pulsed operation averaged over the time produces the same heating up of the target material. Since the residence time of a fluid particle in the target zone amounts to about 200 ms, heating up takes place within 20 time intervals with a pulse repetition time of 10 ms. Related to the mean temperature increase of the target material of 84 °C, the mean temperature rise produced by one pulse thus becomes about 4 °C/pulse. If one calculates this heating up for the maximum calculated temperature rises in the center of the target, extreme values of about 15 °C/pulse are obtained. This is the maximum conceivable temperature variation of the axial temperature rise and it will be neglected here.

Regarding the target geometry the following two cases were distinguished:

- The simple version of a mere cylinder target. The funnel shaped entrance zone of the hollow jet target is neglected.
- The hollow jet target with the funnel shaped entrance geometry is taken into account.

The calculations were made with the HEATING 4 computer code /4/. The temperature distribution evaluated for mere cylinder geometry in the axial and radial directions and target powers of 4.2 MW and 2.8 MW has been represented in Fig. 2. The upper part shows the development of the maximum temperature along the target axis, the lower part the temperature in the hottest cross section for z = 60 cm. The following can be noticed:

- The temperature rises against the inlet temperature increase with growing distance from the target surface, corresponding to the axial heat release. The maximum temperature occurring on the target axis is about 635 °C for Q = 4.2 MW and not more than 480 °C for Q = 2.8 MW.
- The target periphery roughly stays at the level of the inlet temperature. Within the target length considered, it is therefore of no importance for heat transport. The upper diagram also shows data on the saturation pressures, which are identical with the admissible vacuum in case the evaporation of target material is to be avoided.
- If one compares the temperatures calculated for the target surface with the related saturation pressures, it can be recognized that here a much higher vaccum is admissible than the supposed vacuum of 10^{-3} torr.
- If one considers the maximum temperature occurring in the center of flow as the saturation value and compares it with the related saturation pressure, one finds that for a mere cylindrical target a vacuum of 10^{-3} torr is feasible even at the end of the target.

Some of the target material leaving the nozzle is hit by the proton beam even before it develops into the full jet. This means that heat is released in the entrance zone. The calculations performed show also for this example that a vacuum of 10^{-3}mm Hg is feasible. From the computations based on these very conservative assumptions, the evaporation of target material on the target surface can be ruled out. At the end of the target the saturation temperature corresponding to the 10^{-3} torr vacuum is attained by computation only for Q = 4.2 MW on the current filament running along the target axis. Thus, local boiling might occur as a mere hypothesis. Nevertheless, evaporation can be ruled out in practical application by:

- increase of the target flow rate,
- surface tension effects,

- slight flow congestion in the lower target zone (a suitable device has been tested),
- a different radial power distribution of the incoming proton beam.

2.2 Fluiddynamic Design Calculations

2.2.1 Theory of Flow Passage Through the Target /5,6/

The determination of the location where the hollow jet coalesces in a full, free falling jet is of main interest. The calculation model is devided in two parts. In the first part the flow in the nozzle is presumed to be friction dependent. In the calculation model of the second part, which describes the flow outside of the nozzle, the motion is assumed to be frictionless. Both models are coupled by the corresponding initial and boundary conditions.

The mathematical investigations base on the model shown in Fig. 3. The liquid flows under the angle α out of the ring gap with the width b_o and moves along the nozzle wall under the influence of the gravitation g. The fluid leaves the nozzle with the angle β; r_o is the inner radius at the inlet of the nozzle, r is the variable radius which has to be determined, c_r and c_x are the velocity components, b is the variable width of the liquid film, p signifies the pressure. It was the aim that the form of the nozzle should be determined in such a way that the contour would reflect the natural motion of the flow. That is, the form of the nozzle is not presupposed, but the contour and the hollow jet result from the influences of the pressures forces, the surface tension, the viscosity, the gravity and of the inertial forces.

The solution of this problem is given by the Navier-Stokes-Equations. In addition, the following assumptions are made:

- the fluid has Newtonian properties,
- stationary flow field,
- the material parameters, as the density g, the dynamic viscosity μ and the surface tension σ are constant,
- the radius of the nozzle inlet r_o is much greater than the width b_o of the gap.

With the assumption that the radius r_o is much greater than the width of the gap b_o, we reduce the problem to a boundary layer problem.

Usually, the problem is treated with dimensionless variables. The following combinations were chosen:

- radius ratio $R = r/r_o$: $R_1 = r/r_1$
- width of the liquid film $B = b/b_o$
- axial and radial velocity $C_x = c_x/c_{x_o}$; $C_r = c_r/c_{x_o}$
- axial coordinate $X = x/r_o$: $X_1 = x_1/r_1$
- the coordinate in normal direction $\eta = z/b$

After the introduction of these dimensionless parameters, the Navier-Stokes-Equations have the following integral form:

Radial Equation of motion

$$\frac{d}{dx}\left|\frac{dR}{dX}\int_o^1 C_x d\eta\right| + \frac{1}{We_0} = 0$$

Axial equation of motion:

$$\frac{d}{dX}\int_0^1 B\, C_x \left|C_x(\eta=1,X) - C_x\right| d\eta - \frac{dC_x}{dX}(\eta=1,X)\, B \int_0^1 C_x\, d\eta = \frac{r_o/b_o}{B} \cdot T - \frac{B}{Fr_0^2}$$

The equation of the conservation of mass is written as

$$RB \int_0^1 C_x\, d\eta = 1$$

So we are able to determine the three unknown variables: The radius ratio, the axial velocity and the width of the liquid film. Herein is T the wall shear stress, which is described by the law of Stokes for the laminar flow case:

$$T_\ell = \frac{1}{Re_0} \left.\frac{\partial C_x}{\partial \eta}\right|_{\eta=0}$$

In the turbulent case, T is described by the empirical friction law of Blasius:

$$T_t = \frac{0.03955}{(B\, Re_0)^{1/4}} \left(\int_0^1 C_x\, d\eta\right)^{7/4}$$

The dimensionless investigation produces a universal graph of the symmetrical nozzle wall, which can be described by the following characteristical parameters:

Geometric ratio	r_o/b_o
Reynolds number	$Re_o = \rho c_{x_o} b_o/\mu$
Weber number	$We_o = \rho c_{x_o}^2 b_o/\sigma$
Froude number	$Fr_o = \sqrt{c_{x_o}^2/r_o g}$

They represent the ratio of inertial forces to friction forces, of inertial forces to surface tension and of inertial forces to gravitation forces.

The problem to describe the flow outside of the nozzle is solved by the specification of a balance of forces for a mass element. The balance yields the equations for the motion in radial as well as in axial direction and for the conservation of mass.

Differential equation of motion in radial direction:

$$\frac{d^2r}{dt^2} = \frac{p_i - p_a}{\rho b} - 2\frac{\sigma}{\rho b r}$$

in axial direction:

$$\frac{d^2x_1}{dt^2} = g\ .$$

conservation of mass:

$$c_{x1} r_1 b_1 = c_x r b\ .$$

After the substitution of the time variable t by the parameter for the location x, we receive the differential equation for the form of the hollow jet:

$$\frac{d^2R_1}{dX_1^2} + \left(1 + \frac{2}{Fr_1^2} X_1\right)^{-1} \frac{1}{Fr_1^2} \frac{dR_1}{dX_1} - \left(1 + \frac{2}{Fr_1^2} X_1\right)^{-1/2} \left|Eu_1 \frac{r_1}{b_1} R_1 - \frac{2}{We_1}\right| = 0\ .$$

Again we have the characteristic parameters refering to the coordinates: The Froude number and the Weber number. They are completed by the Euler number which is the ratio of pressure forces and inertial forces.

Euler number $Eu_1 = (p_i - p_a)/\rho c_{x1}^2$

modified Froude number $Fr_1 = \sqrt{c_{x1}^2/r_1 g}$

modified Weber number $We_1 = \rho c_{x1}^2 b_1/\sigma$

Some theoretical results are shown in Fig. 4. In the graphs the mean contour of the jet R is plotted against the axial length X as function of the Reynolds number and the Euler number. We see that the contour of the nozzle is widened if the viscosity is reduced. For a reduction of the Froude number, for example by minimizing the flow rate, we also have a widening effect. If the surface tension increases the Weber number will decrease and the location of the contraction will move in upstream direction. For a given nozzle contour the location of coalescence moves also in upstream direction when the Euler number decreases.

2.2.2 Experimental Investigations into the Flow Behavior of the Hollow Jet Target

The theoretical investigations into hollow jet flow allow to evaluate the contour of the hollow jet and hence the size of the nozzle; besides, the axial location of coalescence can be determined where the hollow jet forms the full jet for given operating conditions. The theory does not provide any statement about the flow events occurring in detail at the location of coalescence, however, it assumes a stable flow in the direction of the target axis.

For this reason, the aims of the experimental investigations are:

- Validation of the theory concerning hollow jet flow. For technical application, the following items offer special interest:
  - the axial position of the location of coalescence
  - the stabilization of the full jet, and
  - the variations of the flow behavior in case of deviations from the point of operation.
- Investigations of the flow events around the location of coalescence. To support the thermodynamic calculations, the following items are of interest:
  - proof that no dead water zones will be formed
  - size of the local axial velocities, and
  - the turbulent fluctuations of velocity.

Water Tests on Hollow Jet Contour

The investigations were first made on 1 : 2.5 model scale with the H_2O test facility. The nozzle under investigation was connected to a cylinder shaped annular gap. The liquid surface within the nozzle and outside the full jet is exposed to atmospheric pressure, which means that the Euler number is Eu = 0. The nozzle in the H_2O-experiments are made from plexiglass so that the flow within the nozzle can be observed and the location of coalescence downstream of the end of the nozzle can be well determined.

The test facility with the true-scale nozzle was similar in design. The test rig and a test section of these experiments are represented in Fig. 5.

An optical impression of the flow phenomena occurring around the location of coalescence of the hollow jet into the full jet (x/r_o) is given by Fig. 6. With the nozzle geometry remaining unchanged (r_o/b_o; α), the flow (Froude number) was subject to variations. These photographic pictures show that with the Froude number getting greater the location of coalescence gets more and more approached to the end of the nozzle. The quantitative results have been entered in the diagram as $Fr = f(x/r_o)$ and compared with the theoretical values.

Summarizing, the following statements can be made on the basis of the previous H_2O experiments:

- The location of coalescence determined in the experiment are well consistent with the theoretical predictions in both test geometries.
- With the variation of the Froude number the location of coalescence is displaced. However, a variation of flow assumed for target operation of ±5 % of the nominal flow has practically no influence on the location of coalescence.
- Obstructions expressly introduced into the flow downstream of the end of the nozzle have no impact on the preceeding flow. By contrast, obstructions provided in the flow upstream of the nozzle exert an influence on the stability and conditions of the effluent portion of the full jet. Therefore, the development of the upstream flow and the 180°-flow reversal must be further studied with a view to their feasibility in order to optimize the dimensions of the target head.

Measurement of the Velocity Distribution and of the Turbulent Flow Fluctuations in the Zone of Full Jet Development

In the zone of full jet development flow conditions appear which cannot be recorded theoretically. Since at this point maximum heat releases take place at the same time, the flow passage must be studied in more detail in order to make a realistic thermodynamic design.

- Knowledge of the velocity distributions allow to draw conclusions regarding possible wakes or dead water zones, and above all to provide evidence for the perfect flow passage through this target area.

- Knowledge of the turbulent velocity fluctuations allow to derive indications of the degree of coolant cross mixing and hence of the turbulent heat exchange. These effects decisively contribute to reducing local temperature maxima and, in general terms, to the equalization of temperatures.

A picture of the actual flow conditions in H_2O flow was obtained by the following methods:

- First color tracers were introduced into the flow and their diffusion and transport followed up by a film camera. Then first measurements of the mean velocity distributions were made using Pitot probes. The measured velocity distributions are representative only at considerable distance from the location of full jet development.

On account of high flow turbulences consolidated statements are possible only by use of the Laser-Doppler Anemometry (LDA) allowing contactless and hence non-intrusive measurement of the longitudinal and transversal velocities and of the turbulent exchange variables /6/. Fig. 7 gives an impression of the whole facility. An important result from the comprehensive experiments is shown in Fig. 8. Measured axial velocities are represented as a function of the radial probe position for different distances z from the location of coalescence. It can be noted that for z = 4 mm a local flow reduction of about 20 - 30 % of the mean velocity can be expected on the flow axis and that this will be balanced out after about 15 mm of flow path. Consequently, the previous investigations have shown:

- At the point of coalescence a finite velocity component prevails which is not indicative of any reflows and dead water zones.

- The measurements yield intensive turbulent velocity fluctuations indicative of a high coolant cross mixing.

2.2.3 Investigations into Liquid Metal Flow

To guarantee the transferability of the results from H_2O experiments to the original PbBi fluid experiments are being performed in liquid metal flow on 1:2.5 and 1:1 target geometries. The transferability is examined here because the surface tension of PbBi is greater by about 40 times and the density by about 10 times than the values for water and since in PbBi tests at high vacuum can be performed. The test facilities used in these investigations must be so designed as to meet the requirements of a PbBi flow /7, 8/. Measurement of the liquid metal flow is possible via transit-time and orifice measurements. The outer contour of the target can be recorded via observation windows (saphire windows) and the inner contour of the flow by means of electrical scanning devices. Two PbBi-circuits will be provided for the investigations, both of them already operating. They consist of the storage tanks, the pumps, the test sections and the connecting pipe work with heating and insulation. Typical instrumentation for liquid metal systems is being installed and the loops are characterized as follows:

	PbBi Circuit I /7/	PbBi Circuit II /8/
Type of pump	Centrifugal	Centrifugal
- delivery $|m^3/h|$	5	100
- delivery head $|m|$	3	5
Scale of test section	1:2.5	1:1
Nominal pipe width $|mm|$	25	100

Circuit I (Fig. 9) mainly served to study the handling of PbBi and the eligible instrumentation; it was modified for accommodation of the test sections, scale 1:2.5. Circuit II (Fig. 11) serves to investigate the true-scale test section and, more generally, as a demonstration facility for operation with PbBi. So far two test sections have been designed and fabricated for use in PbBi. The test section I, scale 1:2.5, was already thoroughly examined in water flow and is presently being used in PbBi flow. The test section II, true scale, was likewise investigated in H_2O flow and is presently being adapted to operation in PbBi flow. The investigations have so far produced the following result:

- A stable hollow jet can be generated; this is shown by the photograph of the outside structure of the PbBi jet (Fig. 10).

- The location of the coalescence slightly differs from the results of H_2O experiments with the same test section for the Froude numbers under consideration, which can be explained by the higher Reynolds number and Weber number applicable here.

These first measurements in PbBi flow are supplemented by further parameter studies. They are primarily performed in the PbBi circuit II which allows flow passage through the target at the nominal flow aimed as for the spallation neutron source.

3. ALTERNATIVE CONCEPT OF A HORIZONTAL LIQUID METAL TARGET

3.1 Basic Concept and Problems Involved

The liquid metal concept with flowing PbBi eutectic or pure Pb discussed for the target station of the SNQ allows in principle different target geometries and hence the adaptation to the requirements on geometry resulting from neutron physics. The thermo- and fluiddynamic investigations described before primarily related to a target geometry shaped as a vertical upright cylinder target and the feasibility of the latter as a hollow jet target. However, the configuration of the target block linked to it gives rise to some drawbacks as regards the users requests. Therefore, the possibility was examined of realizing a liquid-metal target having the geometry of a wheel /2, 9/.

The fundamental concepts and the major aspects for design are:

- A target zone with flow passage is to be generated which is suited for horizontal proton injection. The target shall have a thickness of 10 cm normal to the proton beam and a depth of 60 cm along the proton beam axis. The free liquid surface is realized technically by a flow in a rectangular channel curved so as to form nearly a semicircle. The curvature generates centrifugal forces which detach the flow from the inner channel wall and press it to the outer channel walls. Thus, on the inner curved channel wall downstream of the point of detachment a proton beam inlet hole may be provided.

- Since no "window" shall be placed between the target and the proton beam, a vacuum exists above the target surface. It is assumed to be 10^{-3} torr in this case. Consequently, the transport energy can be obtained solely from the kinetic energy of the fluid itself. This leads to a continuous reduction of the flow velocity in the direction of flow. For reasons of continuity the flow channel downstream of proton beam inlet hole must be always widened (diffuser) until the fluid flows into a storage tank and is returned from there to the side of inflow by means of a pump via a heat exchanger.

- The saturation temperature to be attributable to the pressure of 10^{-3} torr constitutes the maximum limit to be observed of local heating of the target material on the target surface.

- It seems necessary to close the proton inlet aperture for startup and shutdown operation in order to avoid the outflow of target material. This must be investigated by experiments and an engineered solution must be found, if necessary.

From these considerations the tasks are derived for the basic investigations which must precede thorough design activities for the liquid-metal target as a horizontal curved rectangular flow:

- calculation of the temperature distributions in the target.
- determination of the channel geometry required for suitable flow guidance
- determination of channel widening to ensure the axial fluid transport

Questions of circuit operation, cleaning and safety of the facility resemble those of the vertical cylindrical target.

3.2 Thermodynamic Computation

The investigation of the local coolant temperatures serves to prove that evaporation under vacuum of the target material on the target surface can be excluded. The computation models adopted include simplifications (slug flow, no radial heat exchange), so that the results determined must be termed "conservative". The minimum pressure and at the same time the maximum load occur on the target surface. Therefore, the maximum coolant temperature is investigated on the current filament directly on the target surface transversal to the beam axis (z = 0). The calculated maximum local temperatures have been represented as a function of the flow velocity in Fig. 13. At the same time we have entered the maximum coolant temperatures obtained for two possible given inlet temperatures of 200 °C (PbBi as the target material) and 400 °C (Pb as the target material), taking into account the calculated temperature rises, as well as the related saturation pressures. The 10^{-3} torr saturation pressure (corresponding to a saturation temperature of approx. 620 °C) marks the possible range of operation for the given inlet temperatures. Thus, a target of 10 cm diameter yields

- for the inlet temperature of 200 °C (PbBi) a flow rate of about 0.5 m/s and
- for the inlet temperature of 400 °C (Pb) a flow rate of about 1.0 m/s.

These velocities are exceeded in practical application. This means that the calculated admissible heating up levels can be observed without difficulties despite the conservative assumption.

These statements are valid for steady-state power operation and undergo but slight variations in pulsed operation. Each fluid particle is hit by a pulse about three times on its way through the target zone. Those particles which at the moment of proton pulse generation are present in the center of the target surface are heated up most. These considerations provide as the results a maximum temperature increase and decrease, respectively, in pulsed operation, which on an average amounts to about $<\pm 10\ ^{o}C$. Consequently, pulsed operation does not affect the fundamental statements made about heat removal. The calculations show in addition that the fluid guiding channel walls within the target zone remain on entrance temperature.

3.3 Fluiddynamic Design Calculations

3.3.1 The Flow Contour on the Free Target Surface

It is purpose of these investigations to determine the flow contour as a function of the flow velocities for given channel curvatures. The channel curvatures are varied within a range delimited by a maximum outer diameter of 2 m and a minimum inner diameter of 0.2 m. The contour of the target surface was roughly estimated. The fluid is exposed to centrifugal and gravitational forces. The free surface of the fluid is obtained normal to the resultant of the attacking forces.

The surface contour is expressed here as the angel which gives the deviation of the contour from the proton beam axis. This computation model applies for a fluid velocity increasing proportional to the radius of curvature. Since this is not in conformity with reality, the radius of curvature for calculation of the surface contour is taken as the distance a between the center of curvature and the center of the fluid filled channel width (R). The results of this computation are shown in Fig. 12. The possible working range is characterized by the following variables:

- maximum external and minimum internal radius of curvature
- angle of the flow contour $\gamma > 50$ deg.
- maximum flow rate 7 m/s.

It appears that these requirements result in minimum velocities of about 2.0 m/s for the smallest inner diameter and 3.0 m/s for the greatest outer diameter of the channel.

3.3.2 Channel Widening for Axial Fluid Transport

The dependence of the axial reduction of velocity on the hydraulic data of the channel geometry was calculated from the equilibrium of frictional and inertial forces. After 2 m of flow path a reduction of velocity and, accordingly, an increase in the flow area of only about 10 % of the initial values is observed. Consequently, a very slim diffuser with little widening can be used which, practically, does not affect the horizontal extension of the target.

3.3.3 Investigations into the Flow Geometry

The previous investigations into the heat removal have shown that the admissible limit temperatures are observed. The considerations were based on simplified models and methods which have to be supported by experiments before a technically optimum solution can be realized. The said experiments primarily relate to the determination of the flow contour, which is not possible theoretically for the time being.

For the purpose, the test section shown in Fig. 14 has been conceived and built. It is a 1:4 scale model and allows visual observation of the flow. By use of variable internals the question can be studied how to shape the point of detachment and an answer can be given as regards the most significant fluiddynamic variables exerting an influence on the realization of the free surface. The following parameters are being varied in these tests:

- the shape of the flow channel by variation of the outer and inner boundaries
- the location and geometry of the point of detachment by various internals provided at the inner curved channel wall.

In the experiments also variables of operation are investigated in addition to the fluiddynamic ones. They include above all the startup characteristic and the answer to the question whether and, if applicable, where a startup valve must be provided in the proton beam channel.

4. SUMMARY AND CONCLUSIONS

To ensure the safe removal of heat released in the target of a high-power spallation neutron source use of a liquid continuously circulated heavy metal would be eligible. The target may be designed on the principle of the hollow jet flow standing vertical as a cylindrical target with a free surface or lying horizontally as a curved rectangular channel to form a plate shaped target. Accordingly, the proton beam can be supplied vertically or horizontally. The studies have concentrated on global heat transport from the target zone and on the local temperature distributions and the local flow phenomena in the target zone.

The previous thermo- and fluiddynamic investigations into the hollow jet target have furnished the following results:

- By theoretical work a method has been made available which allows to calculate the hollow jet flow, especially the location of coalescense of the hollow jet into the full jet. Use of fluiddynamic characteristics enabled us to represent flow phenomena in a more general way. The theoretical predictions of the flow behavior were validated experimentally by water tests carried out on model and original geometries; they seem to be confirmed by first experiments also for liquid metal flows.

- In other experiments the flow phenomena were investigated at the location of coalescense which cannot be treated by the hollow jet theory, and evidence was provided that no dead water zones are formed and hence fluid evaporation on the surface can be ruled out. The measurements of turbulent variations of velocity indicate a very strong coolant cross mixing which contributes decisively to the radial equalization of temperatures and reduces local temperatures peaks.

- On the basis of knowledge so far gathered, we can make the following general statements:
  . The heat can be safely removed from the target zone.
  . Stable flow passage through the target is feasible.
  . The heat transport circuit and its components can be realized.

These global statements guarantee the basic feasibility of a liquid metal target. Further studies are being concentrated on the target geometries in PbBi flow so as to be able to include as well the range of high Weber and Reynolds numbers and to provide support for the comparison of the results with the theoretical predictions.

The preliminary thermo- and fluiddynamic computations relating to the realization of a liquid-metal target with the geometry of a horizontal, curved rectangular channel show:

- The flow velocity in a target formed by a rectangular channel should amount to about $\geq$2.0 m/s so as to enable the development of a sufficiently steep flow surface around the window.
- At this velocity safe heat removal without local superheat of the target material is guaranteed.
- The transport back of the liquid metal calls for a diffuser with about 10 % widening.
- From thermo- and fluiddynamics no indications have been derived which would raise doubts concerning the feasibility of the target geometry discussed in this paper.

However, more in-depth theoretical, experimental and design work will be required to optimize the system in technical terms; this concerns above all the following items:

- Geometry of the flow guidance within the zone of flow detachment upstream of the window.
- Flow phenomena and surface contour downstream of the target zone.
- Overall configuration of the design.

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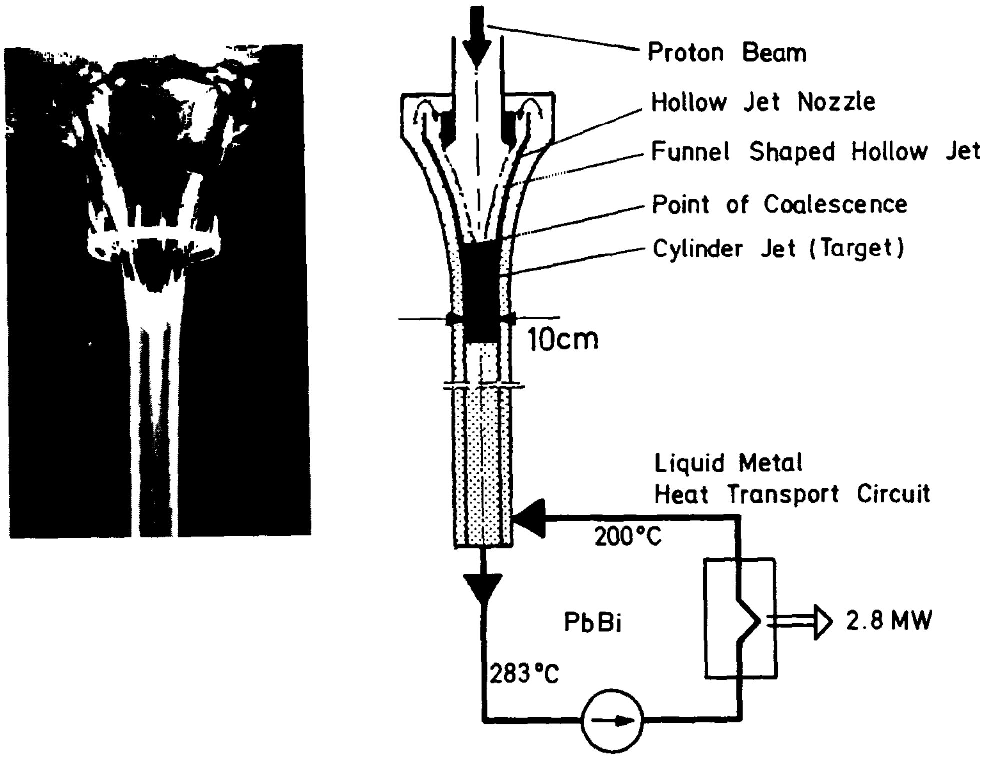
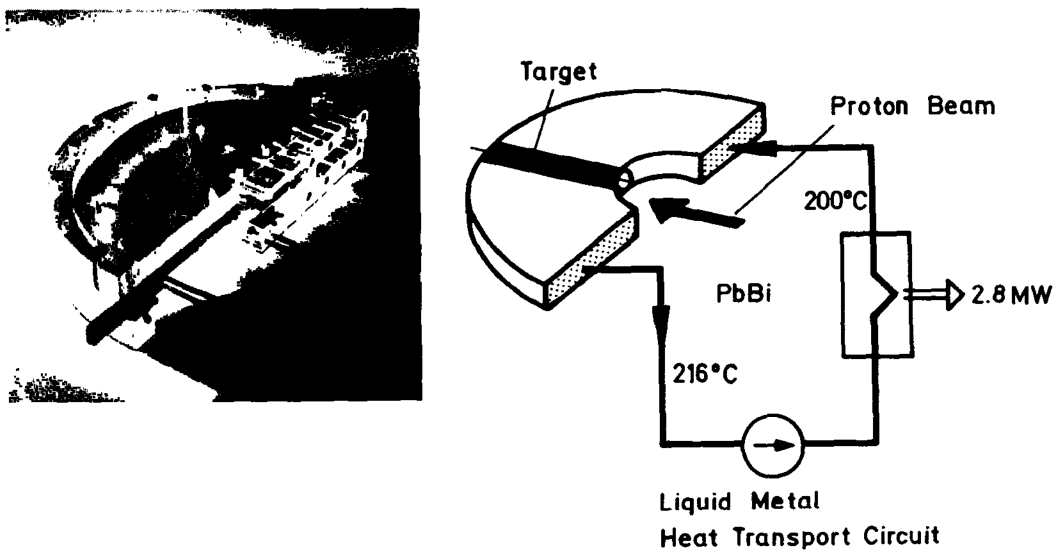


Hollow Jet Target - Cylinder Type



Flat Channel Target - Disc Type

Fig. 1 Liquid Metal Targets (LMT)

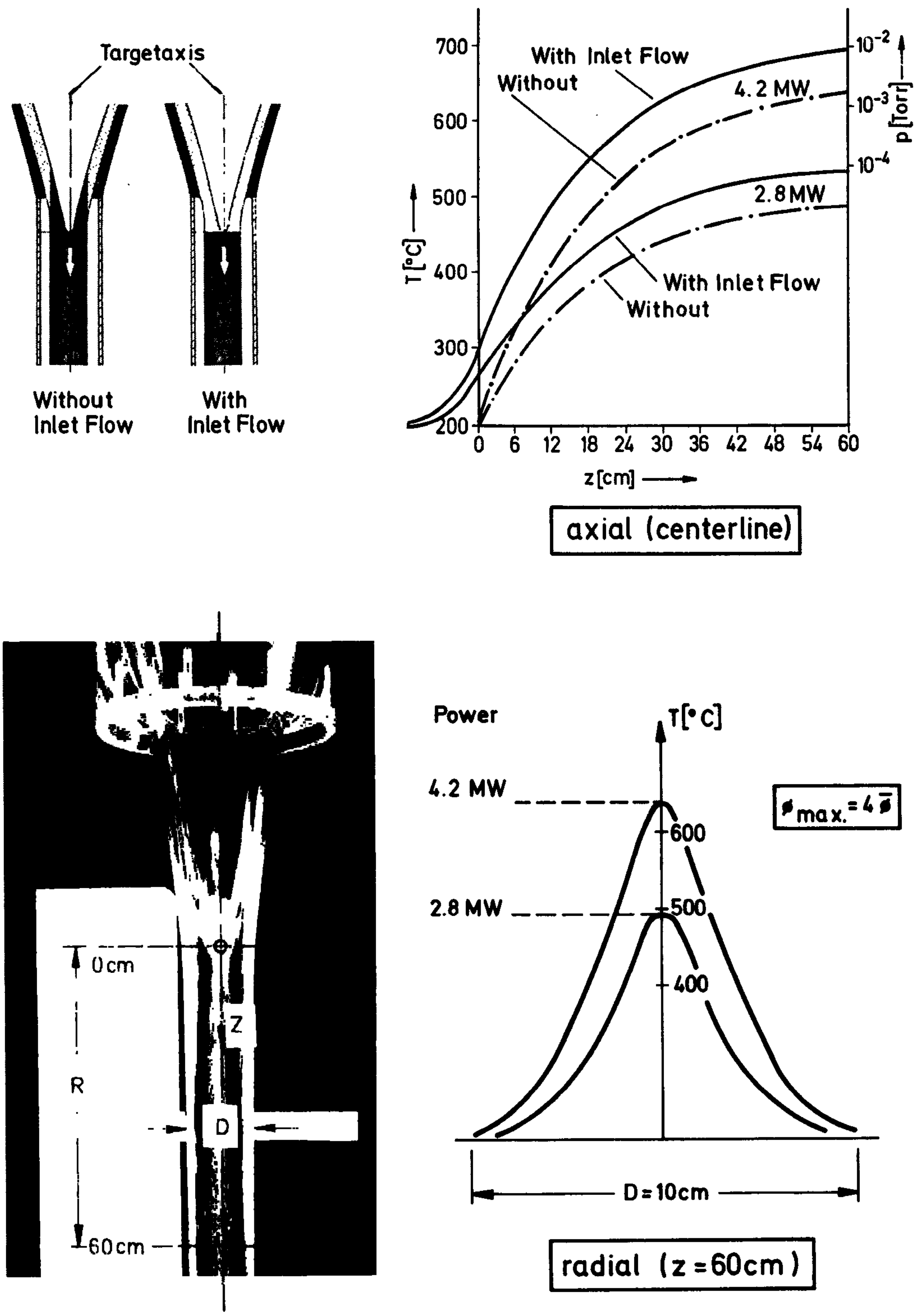


Fig. 2 Temperature Distribution in LMT - Cylinder Type

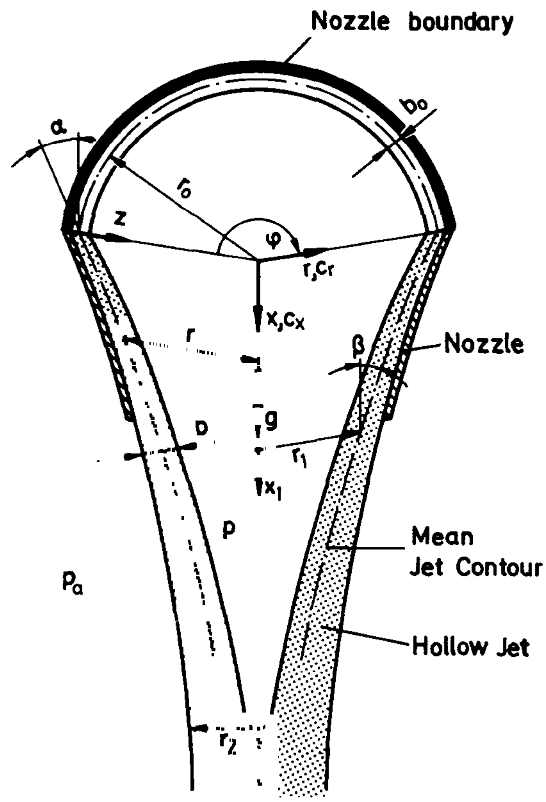


Fig. 3 Mathematical Model

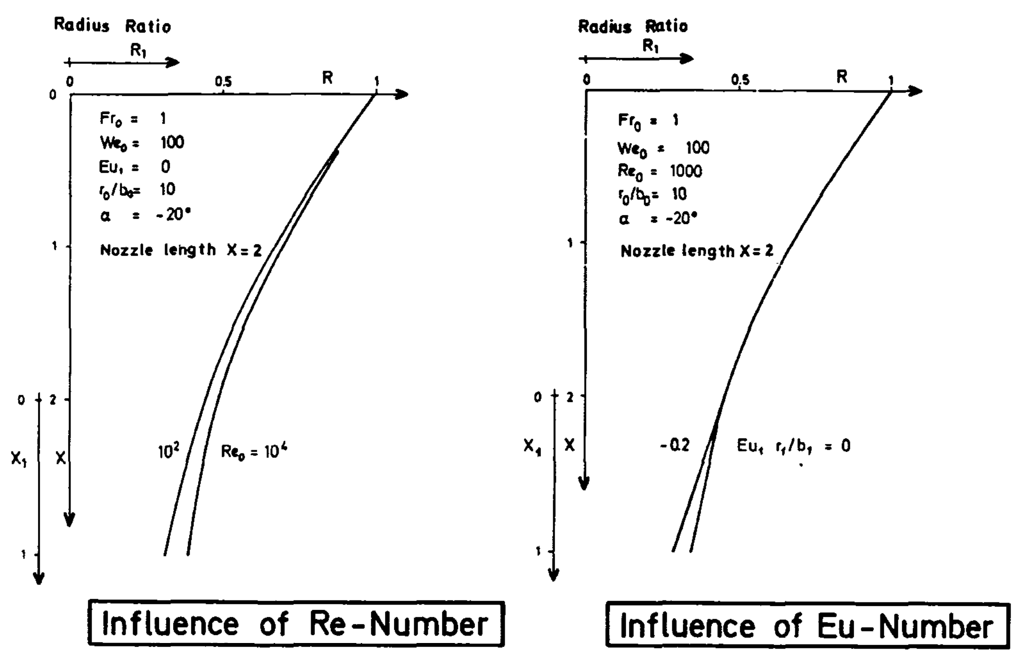


Fig. 4 Calculated Mean Nozzle Contours

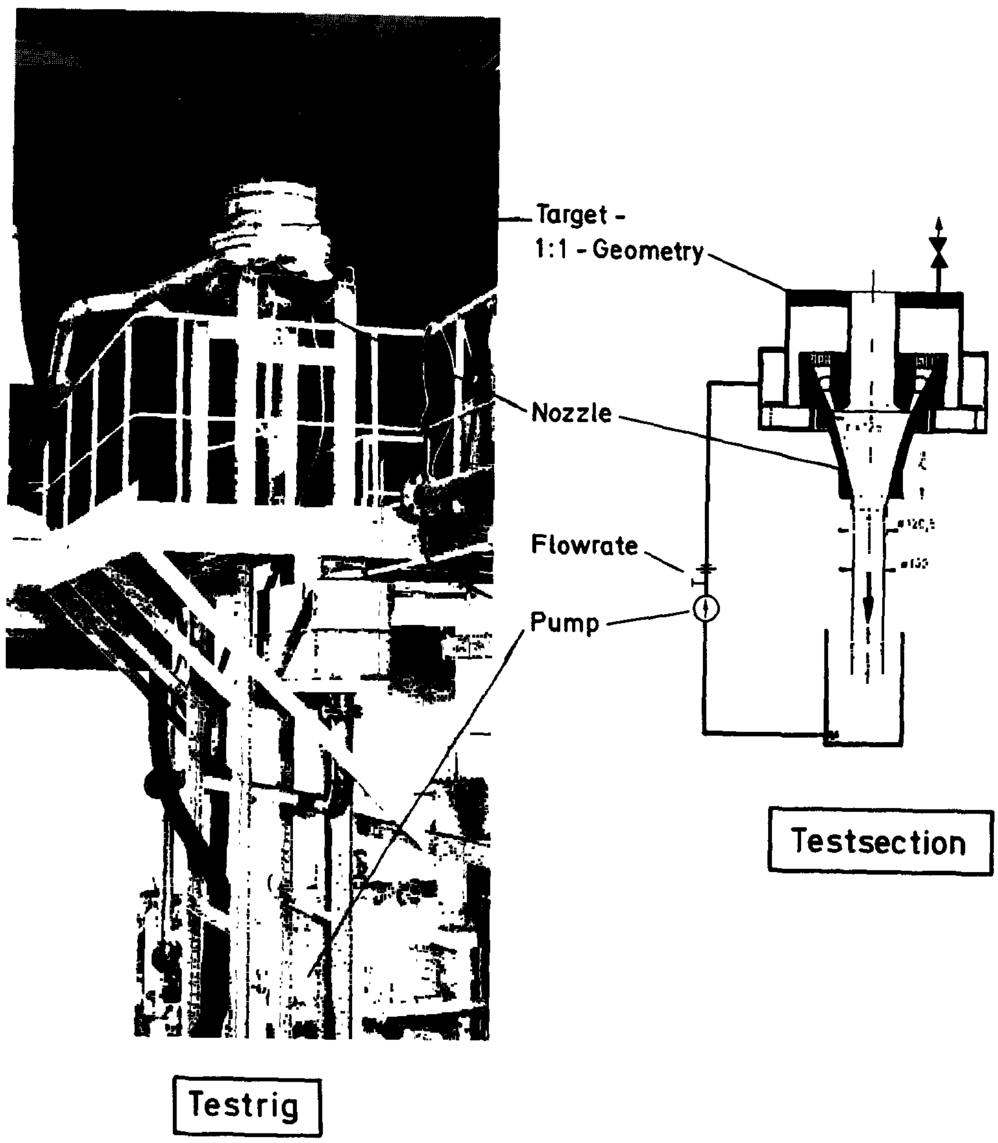
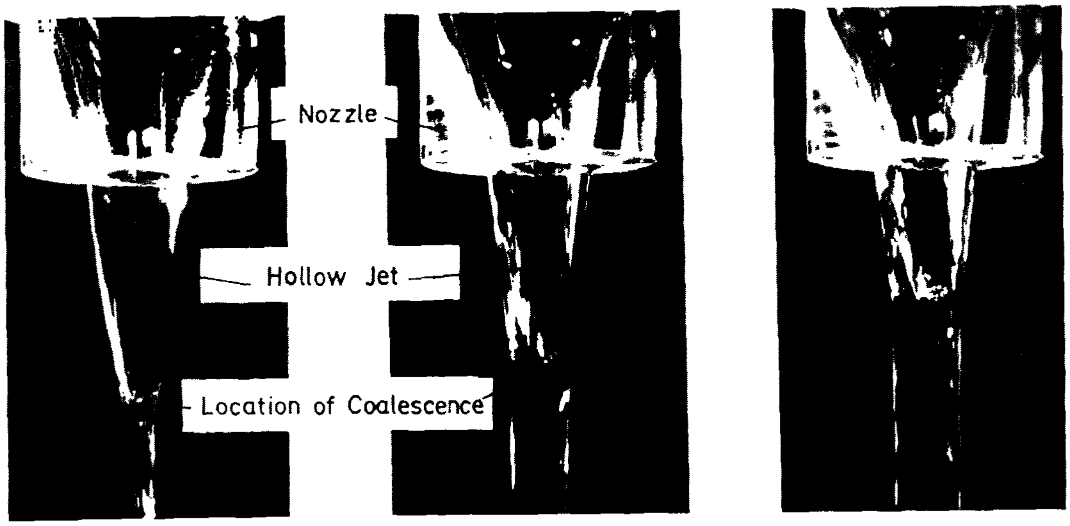


Fig.5 Experiments in H_2O Flow



Fr =0.4 1.15 1.6

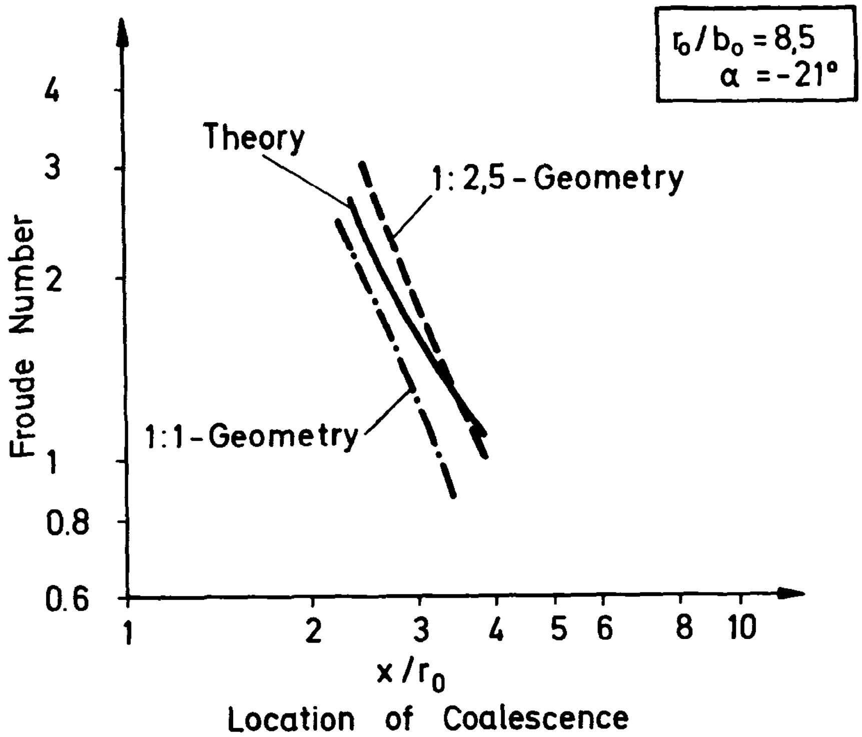


Fig. 6 Flow Behavior of Hollow Jet - Influence of Froude - Number on Location of Coalescence

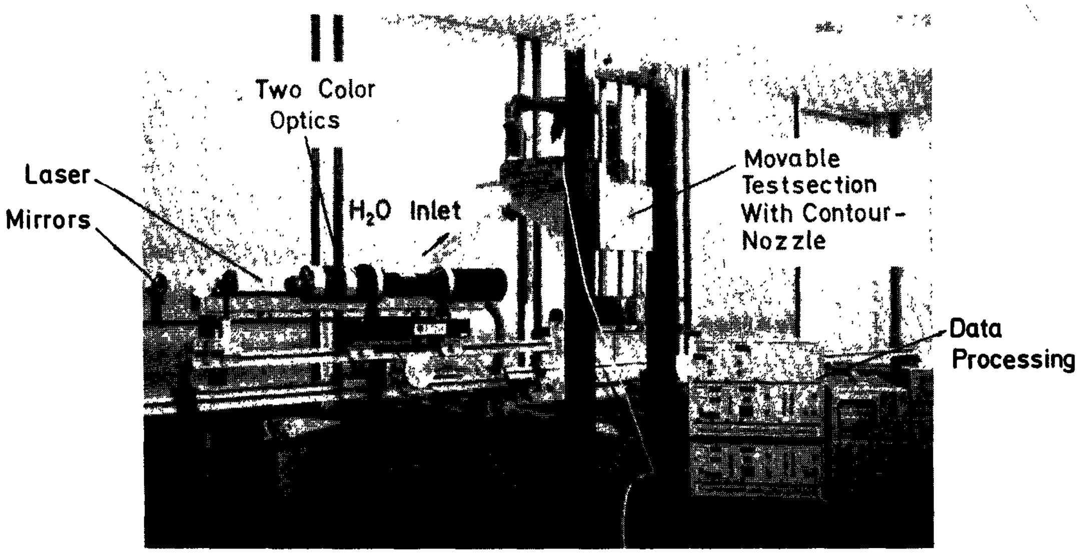


Fig. 7 Laser Doppler Anemometry - Test Arrangement

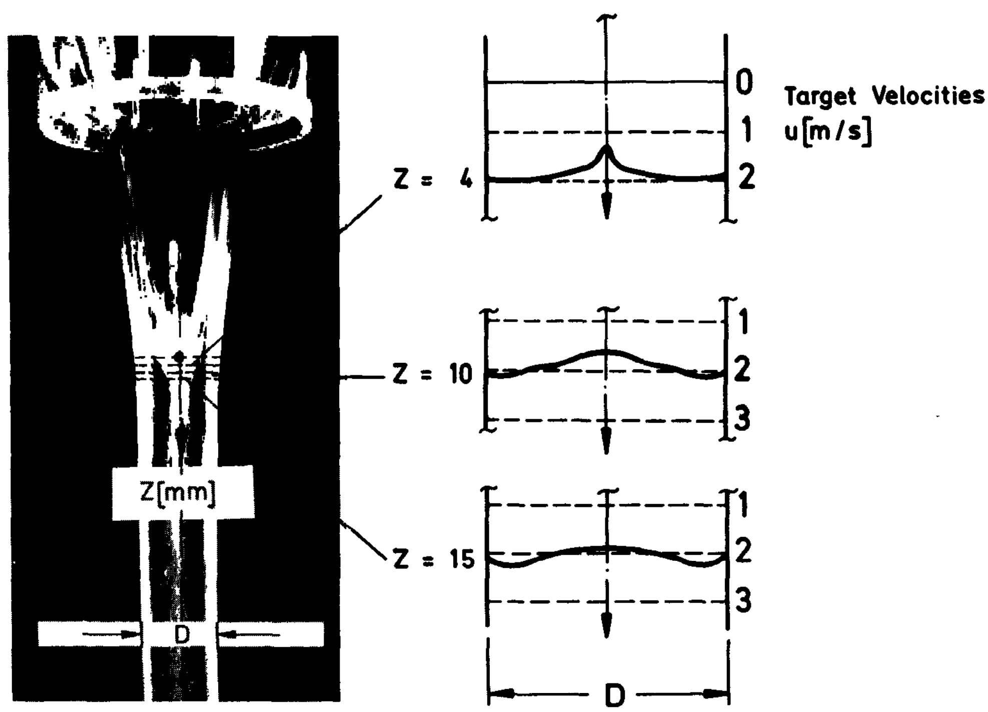


Fig. 8 Local Velocity Distribution near the Point of Coalescence ($Fr = 1.4$; $r_0/b_0 = 5$; $\alpha = -21°$)

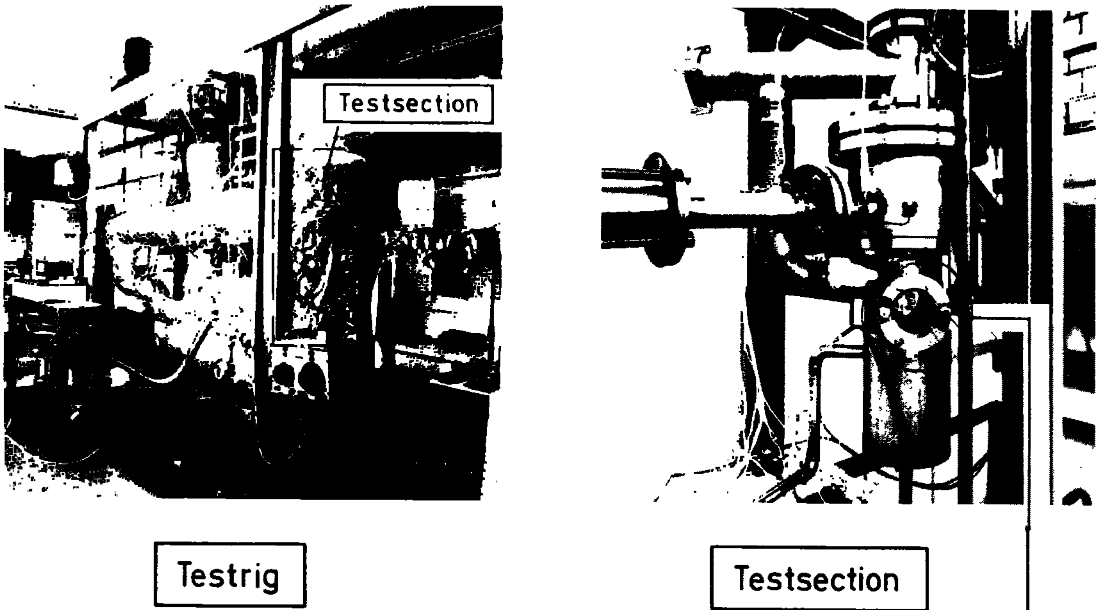


Fig. 9 PbBi - Circuit I - Basic Experiments

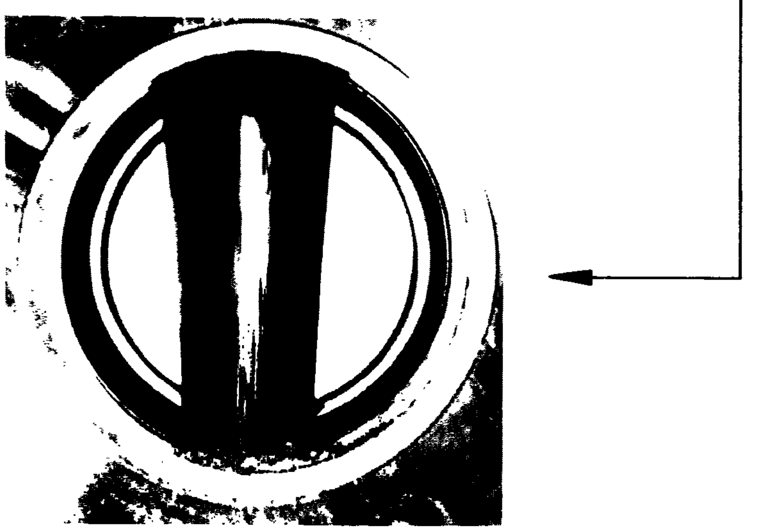
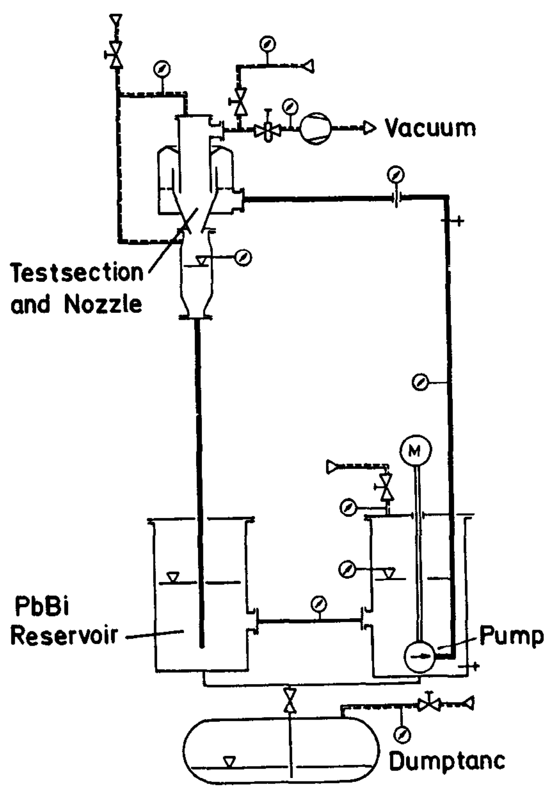


Fig. 10 Outer Contour of PbBi - Jet

PbBi - Testsection:
- Installed in H_2O-Rig -



PbBi-Rig

Fig. 11 PbBi Circuit II - Demonstration

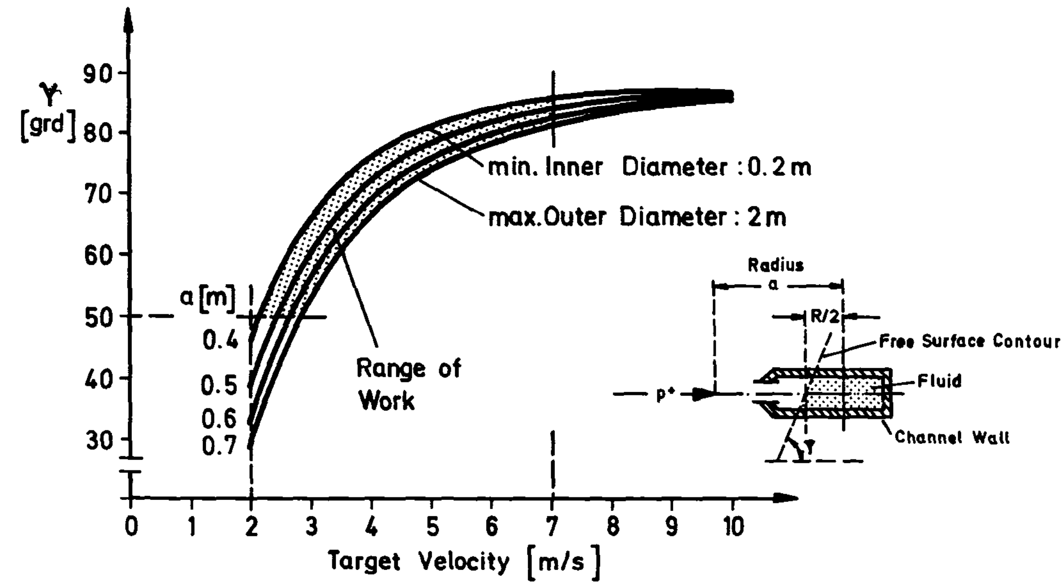


Fig. 12 Angle of Free Target Surface for Different Flat Channel Radia and Fluid Velocities

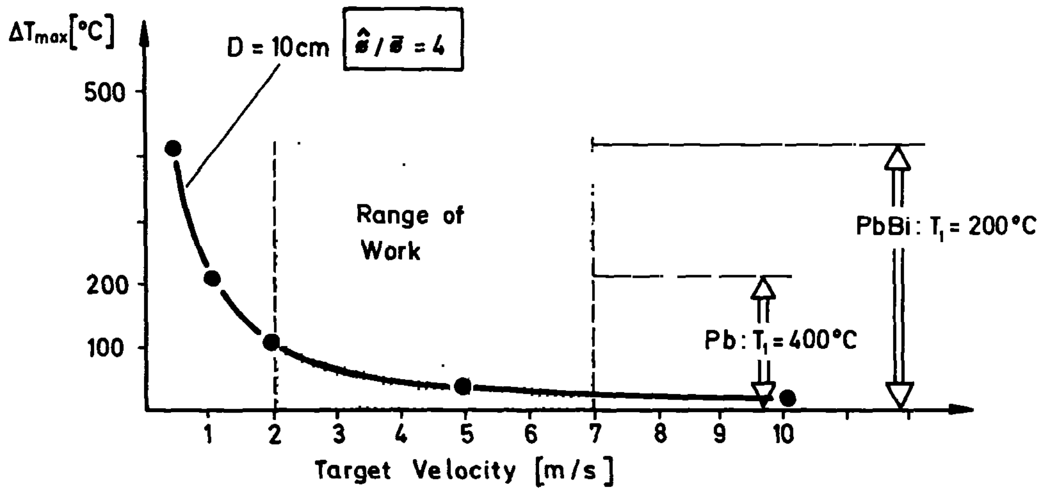


Fig. 13 Maximum Local Fluid Temperatures as Function of the Fluid Velocities (Q = 2.8 MW; z = 0 mm)

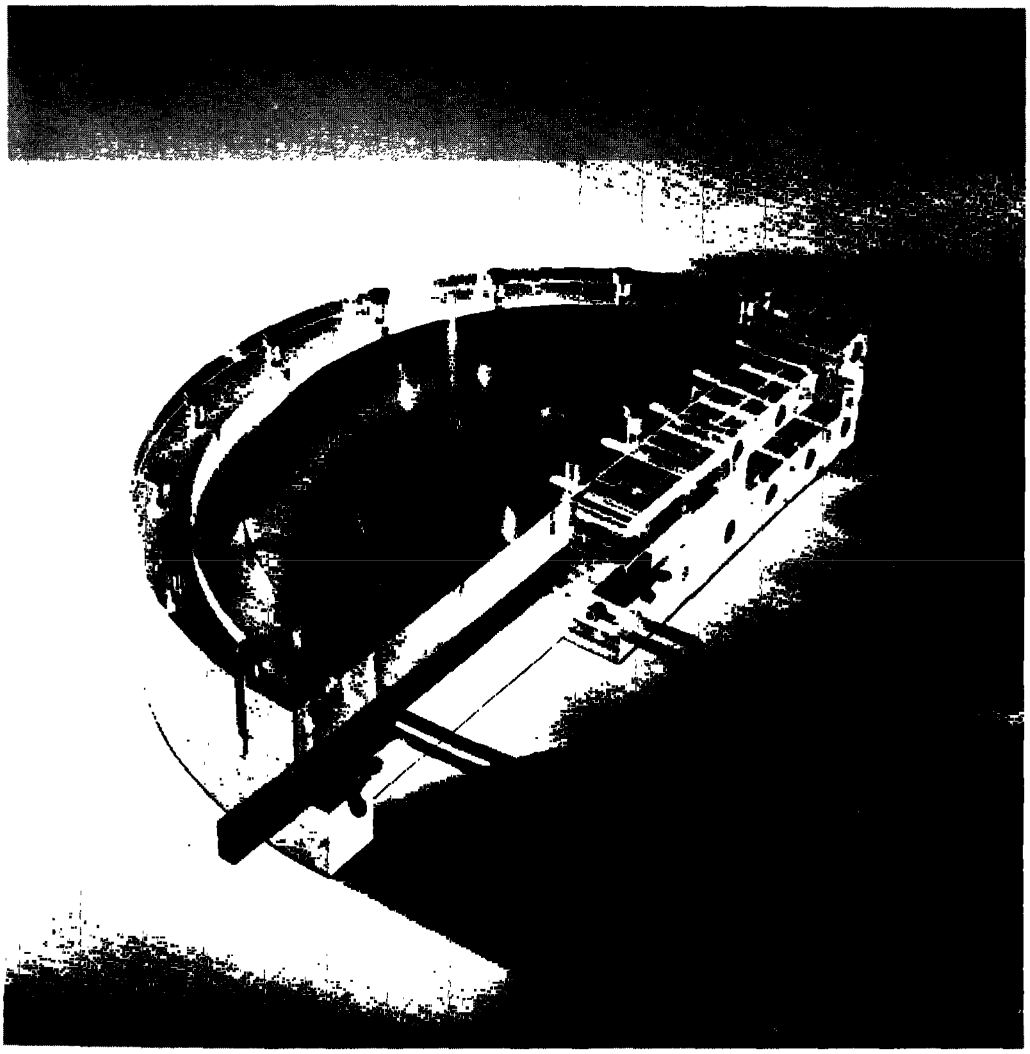


Fig.14 Experimental Proof of Flow Behavior in Flat-Channel Target - Testsection