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AN EXPERIMENTAL INVESTIGATION OF MASS FLOW CHARACTERISTICS OF LAVAL NOZZLES WITH TRANSVERSAL INJECTION THROUGH AN ANNULAR SLOT IN THE SIDE WALL

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Abstract—Measured values of the hydraulic discharge coefficient and the critical mass flowrate are presented. Experiments have been carried out on three Laval nozzles over the following range of flow operating parameters at the inlet of the nozzle: pressure—4 and 8 MPa; water subcooling—from 0 to 50°C; quality of the two-phase mixture—from 0 to 1; and steam superheating—from 0 to 30°C. Transversal injection causes a maximum decrease (30–40%) in the critical mass flowrate at the point corresponding to the discharge of saturated water. Transition from discrete holes to an annular slot in the side wall leads to some increase (up to ~10%) in the critical mass flowrate, while the hydraulic discharge coefficient remains practically constant. The increase in width of the annular slot from 2.57 to 4.59 mm does not cause any systematic change in the transversal injection efficiency. A decrease in length of the cylindrical throat from 156 to 5 mm leads to an increase (~12–20%) in the transversal injection efficiency and to a decrease (~7–12%) in the hydraulic discharge coefficient

Key Words. Laval nozzle, flashing, choking, two-phase flow limiters

INTRODUCTION

The loss-of-coolant accident (LOCA) caused by a primary system break is one of the most urgent problems of nuclear power plant safety. For certain water-cooled reactors, mass flow limiters shaped as axisymmetrical Laval nozzles are often applied to limit the rate of loss of coolant. These devices provoke flow choking when the critical flow regime is reached. As shown by Gabaraev *et al.* (1983, 1989). Laval nozzles with transversal injection of the coolant flow through a circumferential arrangement of discrete holes in the side wall are a promising improvement on these devices. An example of such a mass flow limiter installed in the distribution group header of the RBMK reactor is shown in figure 1. Measured mass flow characteristics of 12 Laval nozzles with holes in the side wall indicate the possibility of an effective decrease in the critical mass flowrate by using transversal injection. However, questions about the differences in the hydraulic and critical flow characteristics in the case of annular slots instead of discrete holes in the side wall still remain unanswered.

EXPERIMENTAL RESULTS

In the present paper, the tests of three Laval nozzles with transversal injection through annular slots with differing lengths of the cylindrical throat L_{thr} and widths of the annular slot δ are presented. The geometry of these nozzles is shown in figure 2 and in table 1. The nozzles have identical inlet converging sections shaped as a quarter of circle with a radius R of 30 mm. Each has a minimal diameter d_{thr} of 20 mm. The annular slot is placed at the very beginning of the elongated inlet section; the jet is injected normally to the axis of the nozzle. It is shown in table 1 that the nozzles investigated have practically the same geometry for the outlet diverging sections. This table includes the dimensionless flow area of the annular slot $F_{\mathrm{inj}}/F_{\mathrm{thr}}$, defined as the flow area of the annular slot F_{inj} divided by the flow area of the nozzle throat F_{thr}.

Experiments have been carried out for steady conditions in the following range of flow operating parameters at the inlet of the nozzle: pressure $P_{\mathrm{in}} = 4$ and 8 MPa; water subcooling—from 0 to

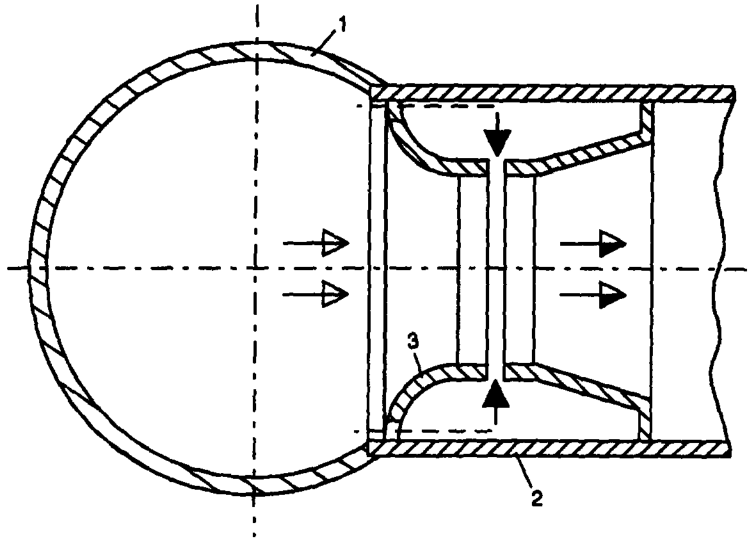

Figure 1. Nozzle mass flowrate limiter in the distribution group header (DGH) of the RBMK reactor: 1, discharge header; 2, DGH pipe; 3, nozzle; —▷, primary flow; —▶, secondary (injected) flow; —⊳, total flow.

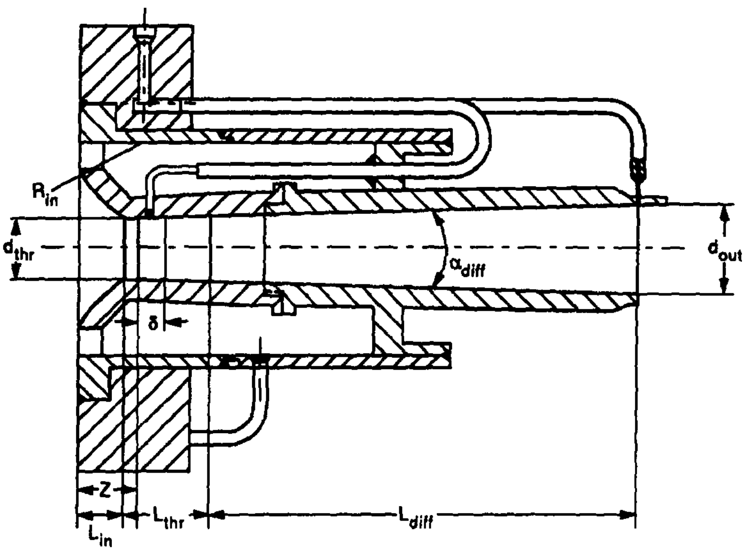

Figure 2. The design of test nozzles with the injection through the annular slot in the side wall (the slot is all around the periphery).

50°C; quality of the two-phase mixture—from 0 to 1; steam superheating—from 0 to 30°C. The test facility and procedure are described by Kevorkov *et al.* (1977). Experimental uncertainty is within ±2% for pressure, ±1.4°C for temperature and ±7% for mass flowrate.

The test nozzles were previously calibrated with water at an initial pressure of 4 MPa and a temperature of 170°C. Table 1 lists the values of the hydraulic discharge coefficient μ, which is

Table 1. Geometric and hydraulic characteristics of the tested nozzles

Nozzle No.	L_{thr} (mm)	δ (mm)	Z (mm)	L_{diff} (mm)	α_{diff} (deg)	F_{inj}/F_{thr}	μ	μ^*
Nozzles Tested in the Present Study								
1	156.3	1.23	31.5	183.2	6°06′	0.24	0.360	0.479
2	5.0	2.57	31.0	180.0	5°54′	0.50	0.334	0.614
3	5.0	4.59	30.0	180.0	5°54′	0.90	0.316	0.614
Nozzle Tested in Gabaraev et al (1989)—8 Discrete Holes, dia = 3.6 mm								
4	156.3	—	32.8	183.2	6°06′	0.26	0.356	0.479

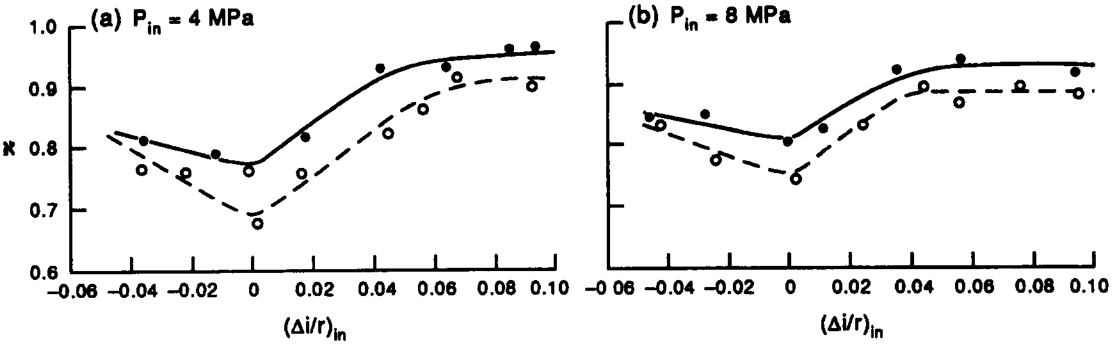

Figure 3. The effect of the configuration of the port in the side wall on the efficiency of transversal injection: —●—, nozzle 1 with an annular slot; --○--, nozzle 4 with discrete holes; in other respects these nozzles have the same geometry.

defined as the actual (measured) mass flowrate divided by the ideal mass flowrate: $\sqrt{2(P_{in} - P_{out})/V_{out}} \cdot F_{out}$, where P_{out}, V_{out} and F_{out} represent pressure, specific volume and flow area, respectively, in the outlet plane of the nozzle. Table 1 also includes for comparison the values of the hydraulic discharge coefficients μ^* of nozzles which have the same geometry but no slots or holes in the side wall. Evidently, transversal injection through an annular slot in the side wall substantially decreases the discharge coefficient in comparison with the nozzle without transversal injection, this effect being more pronounced for wider annular slots or shorter cylindrical nozzle throats.

Table 1 also lists the characteristics of nozzle 4, tested by Gabaraev *et al.* (1989). The geometry of this nozzle is almost identical to that of nozzle 1, but the former has discrete holes of the same total flow area as the annular slot. Comparison of the discharge coefficients of the nozzles shows that discrete holes and an annular slot of equal flow area lead to an identical increase in the nozzle hydraulic resistance coefficient.† This observation is an answer to one of the two aspects of the question about the change in the hydraulic and critical mass flow characteristics of the nozzle due to the transition from discrete holes to an annular slot in the side wall.

It is convenient to consider the second aspect, namely the change in the critical flow characteristics, using the specific critical flowrate ratio for nozzles with and without transversal injection but having almost identical geometry:

$$\aleph = \frac{G_{cr}\,\text{injection}}{G_{cr}\,\text{no injection}},$$

where G_{cr} is the critical mass flowrate divided by the flow area of the nozzle throat F_{thr}. This "ratio" represents the efficiency of transversal injection in decreasing the critical flowrate through the nozzle. The smaller values of $\aleph$ correspond to a more effective mass flowrate limiter.

Figure 3 shows a comparison of the measured values of the transversal injection efficiency for nozzles 1 and 4, differing only in the configuration of the port in the side wall (annular slot or discrete holes). As can be seen, these nozzles reveal close similarity in the efficiency of transversal injection. The characteristic of nozzle 1 is, however, systematically above that of nozzle 4, indicating that discrete holes lead to a somewhat stronger decrease in the specific critical mass flowrate in comparison with an annular slot of the same flow area F_{inj}. This effect is more appreciable at lower pressure ($P_{in} = 4$ MPa) and can reach 10%. Figure 3 shows that both nozzles attain a minimal value of $\aleph$ almost in the vicinity of the point $(\Delta i/r)_{in} = 0$, which corresponds to the discharge of saturated water. The dimensionless relative enthalpy of flow at the inlet of the nozzle $(\Delta i/r)_{in}$ is defined as the difference between the flow enthalpy and the saturated water enthalpy divided by the latent heat of evaporation r.

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†The so-called hydraulic resistance coefficient represents the integral flow loss coefficient corresponding to the total pressure loss due to friction, area change and spatial acceleration.

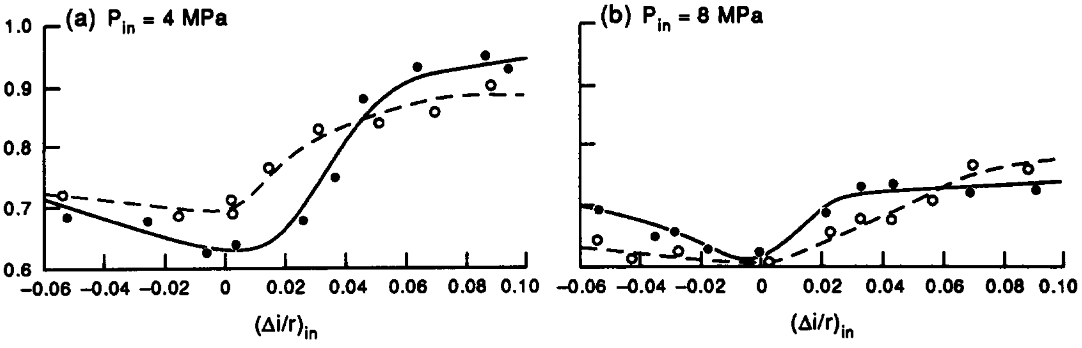

Figure 4. The effect of the dimensionless flow area of the annular slot in the side wall on the efficiency of transversal injection· —●—, nozzle 2, --○--, nozzle 3; these nozzles differ only in the width of the annular slot—2 57 and 4 58 mm, respectively.

Figure 4 illustrates the effect of the width of the annular slot on the efficiency of transversal injection. It can be seen that an increase in the width of the annular slot, namely the transition from 2.57 to 4.59 mm, does not cause any *systematic* change in the critical flow characteristics. These characteristics intersect at some location, depending on the pressure (4 or 8 MPa). As in the case of nozzles 1 and 4, the difference between the values of ℵ for nozzles 2 and 3 can reach ~ 10%. Figure 4 shows that both nozzles 2 and 3 attain a minimum value of ℵ in the vicinity of the point $(\Delta i/r)_{in} = 0$.

The authors suggest that the observed effect of an annular slot on the critical flowrate is explained by the enhanced turbulence connected with the injected flow. Indeed, an enhancement of the flow turbulence causes a decrease in the degree of flow metastability. It is well-known that a decrease in flow metastability leads to lower critical flowrates, approaching those for equilibrium conditions.

As seen from figures 3 and 4,† nozzles 2 and 3 are characterized by a more substantial decrease in the critical flowrate than nozzle 1. This might be due to the influence of the length of the cylindrical throat or of the width of the annular slot in the side wall of the nozzle. Figure 4 shows that the width of the annular slot is not likely to be the cause of this effect. The influence of the length of the cylindrical throat seems a more probable cause. This conclusion is indirectly confirmed by the results of Gabaraev *et al.* (1989), which, for nozzles with discrete holes in the side wall, revealed an increase in transversal injection efficiency due to a decrease in the length of the nozzle throat.

CONCLUSIONS

1. Transition from discrete holes to an annular slot in the side wall leads to some increase (up to ~ 10%) in the critical mass flowrate, while the hydraulic discharge coefficient remains practically constant. This is the case for Laval nozzles with a sufficiently long throat.
2. The increase in width of the annular slot from 2.57 to 4.59 mm does not cause any *systematic* change in the transversal injection efficiency for both values of the pressure at the inlet of the tested nozzles.
3. For all three nozzles with slots in the side wall, as well as for nozzles with discrete holes, transversal injection causes a maximum decrease (~ 30–40%) in the critical mass flowrate in the vicinity of the point corresponding to the discharge of saturated water.
4. The decrease in length of the nozzle throat from 156 to 5 mm leads to an increase in the transversal injection efficiency of 12–20%, while the hydraulic discharge coefficient decrease by 7–12%.

On the whole, transversal injection through annular slots deteriorates the hydraulic characteristic of the nozzle. Vazinger *et al.* (1982) propose to eliminate this shortcoming by installing burst

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†The data cover a broader range than shown in these figures, but remain flat outside the range plotted

membranes in the transversal injection flow path, preventing transversal injection during standard operation of the nuclear power plant.

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