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BOUNDARY-LAYER CONTROL FOR REDUCING
DEPOSITION OF SOLIDS AT A GEOTHERMAL NOZZLE WALL

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June 10, 1976

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ERRATA

Please make the following correction to your copy of UCID-17170:

Page 9

The last part of caption should read:

"....Dimensions are in inches."

Technical Information Department

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SYMBOLS

d_t	throat diameter of nozzle, cm
L	axial length of diverging section of nozzle, cm
m	exponent in Eq. (1)
n	exponent in Eq. (2)
N	local flux of drops to wall, $\text{kg/m}^2\text{-s}$
Re_t	Reynold's number at throat of nozzle
t	local deposit thickness, mm
x	axial coordinate, cm
θ	total divergence angle, degrees

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BOUNDARY-LAYER CONTROL FOR REDUCING DEPOSITION OF SOLIDS AT A GEOTHERMAL NOZZLE WALL

ABSTRACT

Deposition of solids at the wall of a nozzle used to expand geothermal brine may be accounted for by a hydrodynamic model describing eddy formation near the wall. A conceptual design of a nozzle with injection of an annular ring of fluid at the wall is presented.

INTRODUCTION

Lawrence Livermore Laboratory's geothermal energy project concerns a "total flow" process¹ for production of electricity from geothermal brine. In this process, high-temperature and -pressure, two-phase brine expands through a nozzle to convert thermal to kinetic energy. A serious problem encountered in this process is the formation of scale at the walls of the nozzle and other component parts. One method suggested for combatting this problem is to control the hydrodynamic boundary layer near the wall of the nozzle to maintain a clean surface. Feiereisen recently did a theoretical study treating the injection of fluid at the wall of a nozzle.²

This report summarizes the major findings of a search of the two-phase flow literature and recommends an experimental study of the injection of fluid at the wall of a nozzle.

DISCUSSION

Careful inspection of several nozzles, tested at the Sinclair No. 4 geothermal well in the Salton Sea, California,³ yielded some interesting results. Figure 1 shows the shape of a typical deposit at the wall of a nozzle (run N-31-Haveg³). Here, little or no deposition takes place upstream of the throat, while downstream the thickness increases rapidly. The same data, when plotted logarithmically in Fig. 2, result in a straight line. Let us assume that the rate of deposition is proportional to the rate of transport of drops to the wall, denoted by N . Then, we may express the experimental results in the form

Fig. 1. (a) Nozzle contour³ and (b) deposit-thickness profile.

Fig. 2. Same deposit-thickness profile as in Fig. 1, but plotted logarithmically.

$$N \propto x^n, \quad (1)$$

where $n = 0.250$ is the slope of the line in Fig. 2.

Transport to a flat plate is described by the expression

$$N \propto \frac{1}{x^m}, \quad (2)$$

where $m = 1/3$ for laminar flow at high Péclet number,⁴ $m = 1/2$ for laminar, boundary-layer flow at large Schmidt number,⁵ and $m \approx 0.20$ for turbulent flow.⁵ Indeed, if turbulent transport were the only mechanism for transport of drops in a well-behaved flow, the deposit would decrease in thickness with distance downstream according to Eq. 2. Further, there is yet no explanation for the fact that deposition does not take place upstream of the throat. Thus, we may suspect that other mechanisms are important.

Considerable work has been done investigating the hydrodynamic behavior of two-dimensional diffusers. Fox and Kline⁶ found experimentally that as divergence angle increases, the flow separates (as evidenced by the appearance of regions of large transitory stalls, fully-developed stalls, and finally, jet flow). Figure 3 maps these various flow regimes.⁶ It is reasonable to assume that similar flow regimes exist for the conical nozzle; however, no study treating this subject has come to my attention.

Table 1 summarizes experimental conditions used by various researchers in their work with nozzles. This table includes the Reynold's number based on the throat diameter. When data necessary for the calculation of the Reynold's number were not reported, I assumed that the flow was critical and obtained the flow rate from Ref. 8. Since the flow regime map of Fig. 3 is valid only for two-dimensional diffusers, its use for conical nozzles is questionable. Nevertheless, it is noteworthy that 11 of the flow conditions listed in Table 1 fall into the region in which transitory stalls were observed in two-dimensional diffusers.

We may now formulate a qualitative description of the flow near the wall of a conical nozzle. Figure 4 shows a sketch of the situation. Here, a small, laminar boundary layer forms at the throat. Further downstream, this layer becomes turbulent and recirculating, with pairs of eddies appearing near the wall. Eddy formation is a consequence of the adverse pressure gradient in the nozzle. This behavior may be understood by noting that since the pressure at point A (see Fig. 4) exceeds that at B, a secondary flow may arise from A to

Fig. 3. Flow regimes in two-dimensional diffusers.⁶

Fig. 4. Flow near the wall of a conical nozzle. See p. 4 for discussion of pressure at points A and B.

Table 1. Summary of experimental conditions used in nozzle research.

No.	θ (deg)	d_t (cm)	L (cm)	L/d_t	$Re_t \times 10^{-6}$	Fluid	Ref. No.
1	9.5	1.3	4.5	3.5	6.2	*	3
2	2.4-48	2.5-10.2	16-488	1.6-48	0.15-10	Water	6
3	7.0	0.52	6.4	12.3	0.94-4.4	Water/air	7
4	24	0.438	2.83	6.5	1.7-4.3	*	8
5	24	0.252	4.71	18.7	3.9-8.7	*	8
6	5.0	8.08	61	7.6	39-79	Water/N ₂	9
7	7.0	0.51	6.9	14	5.6-11	Water/air	9
8	4.8	3.3	8.9	2.7	0.53-1.5	*	10
9	10.6	1.68	10.2	6.07	0.76-0.95	*	11
10	3.8	0.81	3.0	3.7	0.34-5.6	*	12
11	8	10.2	72.0	7.1	0.29	Air	13
12	23.7	0.640	6.05	9.5	2.2-3.8	*	14
13	17.9	0.640	8.08	12.6	—	*	14
14	12.0	0.640	12.1	19.0	—	*	14
15	12.0	0.902	22.7	25.2	3.3	*	14
16	20	0.64	3.6	5.7	3.11	*	15

* Denotes steam.

B. Thomas¹⁶ presented a similar argument for flow in expansions. Further, the size of the eddies should increase downstream due to a simultaneous decrease in average velocity.

The deposit morphology supports the above hydrodynamic model. Upstream-pointing "bumps" or nodules have been observed,¹⁷ indicating locally high transport rates to the wall. Careful examination of some typical test nozzles³ revealed that the spacing of the "bumps" is extremely close at the throat, where they first appear, and increases with distance downstream. Further, the "bumps" appear to form rings of ridges and valleys around the wall, indicating axial symmetry.

Compressibility and two-phase considerations withstanding, we can now make certain recommendations concerning nozzle design. First, divergence angle and L/d_t should be kept small. (The current test design¹⁵ is most likely too large.) Second, if the flow is well described by the above model,

then removal of the boundary layer either by sucking or blowing may be successful in eliminating the recirculating regions, thus reducing the deposition rate at the wall. The latter option seems to be more feasible, since sucking is likely to clog the withdrawal ports.

A thorough laboratory investigation ought to be conducted to determine the hydrodynamic behavior of a nozzle with blowing at its wall. Such a study might be done either optically (using tracer injection with an optically clear nozzle fabrication material¹⁸) or electrochemically (by injecting a fluid with electrical conductivity different from that of the working fluid and measuring the current to the nozzle wall). The Reynold's number for such an experiment should be the same as that encountered in a geothermal nozzle (see Table 1).

Figure 5 is a conceptual, detail drawing of a nozzle design for injecting an annular ring of fluid at the wall. In the figure, injected fluid passes through a port, A, and on into an annular dispersing cavity, B. Four radial ports, C, feed fluid to a thin annular slit, D, machined at an angle into the nozzle. The axial position of the slit is that point at which the deposit on the test nozzles becomes one-tenth of its maximum value at the exit.

CONCLUSIONS

The rate of deposition of solids at the wall of a geothermal nozzle is proportional to $x^{1/4}$; this phenomena cannot be explained through simple transport arguments. A hydrodynamic model involving eddy formation is well supported by observation of the deposit morphology. The rate of deposition of solids may be decreased by designing the nozzle with both small divergence angle and L/d_t and by injecting fluid at its wall. I recommend a laboratory investigation.

Fig. 5. A nozzle³ with fluid injection at the wall. Injected fluid flows from zone A to D (see p. 8 for discussion).

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