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AN INTENSE NEUTRON SOURCE FACILITY
USING A SUPERSONIC JET TARGET

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ABSTRACT

Investigations are underway to determine the concept feasibility and design criteria for an intense-neutron-source facility using a supersonic-jet target. This target consists of an expansion nozzle where deuterium gas is accelerated to supersonic velocities and an interaction region where a tritium-ion beam interacts with the supersonic jet of deuterium producing the neutrons. The present research is concerned with the experimental and theoretical design of the expansion nozzle and interaction region. Results of an initial experimental test without ion-beam heating are discussed. The numerical solutions for the initial-experiment configuration as well as three additional solutions are also presented.

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INTRODUCTION

The major objective of the national Controlled Thermonuclear Research (CTR) program is to contribute to the nation's energy production soon after the turn of the century. One of the milestones to be passed in this program is a thorough knowledge of the effects of high-level neutron irradiation on materials and insulators that are to be used for the CTR program. The early needs for a high-fluence 14-MeV neutron source to carry out such relevant studies probably can best be met by the supersonic-gas-target approach.

Therefore, investigations are underway to determine the concept feasibility and design criteria for an intense-neutron-source (INS) facility.^{1,2} When developed, the facility will provide a neutron environment for materials testing similar to that anticipated in a fully operational fusion-power reactor, approximately 10^{14} primary neutrons per $\text{cm}^2\text{-sec}$. The INS considered is a continuously flowing system, in which a supersonic-deuterium jet of density approximately 2×10^{19} molecules per cm^3 is used as a target for a tritium-ion beam of 1 ampere.

The system presently under study consists of the co-axial design shown in Fig. 1. The deuterium is first accelerated to supersonic velocities through an annular nozzle, then enters the central duct where it interacts with the tritium-ion beam producing the neutrons. The main deuterium stream continues on to the right and exits through a diffuser, then passes through a heat exchanger and pressure-recovery system before returning to the plenum to complete the flow loop. A small quantity of deuterium escapes into the ion-beam access duct and exits to the left. This deuterium must be differentially pumped to maintain a good vacuum for the tritium-ion beam, separated from the tritium, and returned to the plenum. The primary emphasis of the present research is the experimental and theoretical design of the expansion nozzle and interaction region. The design goal is to minimize the deuterium loss through the ion-beam access duct while maintaining the capability of dissipating large amounts of energy, approximately 300 kw.

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FLUID DYNAMIC MODEL

In order to analyze the expansion nozzle and interaction region, the equations governing the dynamics of the deuterium jet and the tritium-ion beam must be solved. To simplify the problem, the following assumptions are made: (1) the geometry is considered to be two-dimensional, that is, planar or axisymmetric, (2) the deuterium is assumed to be a perfect gas, (3) the viscous effects of the deuterium gas are important in the boundary layer only, (4) the tritium-ion-beam mass and momentum are considered to be negligible, and (5) the ion-beam energy deposition is assumed to be a function of the ion-stopping distance only. Therefore, the equations to be solved consist of the conservation of mass, momenta, and energy equations for the deuterium jet and a relation relating the ion-beam-energy deposition to the stopping of the tritium ions by the deuterium gas.

NUMERICAL METHOD

The equations of motion for the deuterium gas are solved using the computational technique described in Ref. 3. In this technique, the time-dependent, two-dimensional, inviscid, Euler equations are solved using an explicit, second-order, Eulerian, numerical technique. The boundary layer is calculated using the boundary-layer technique of Ref. 4. However, for the results presented in this paper, the boundary layer has been neglected.

The ion-beam energy-deposition relation is satisfied by depositing the ion-beam energy as a function of the deuterium-gas density until the ions are stopped. This ion-beam energy is added to the deuterium gas as thermal energy. This process is repeated at each time step until the solution converges to steady state.

RESULTS

The initial-experiment configuration is shown in Fig. 2. The dashed line on the bottom of Fig. 2 is the cylindrical axis or centerline. This model has been installed in a test stand using hydrogen gas in place of deuterium. The main hydrogen stream leaves the interaction region through the exhaust duct located at the right of Fig. 2 and is then dumped to the atmosphere. The ion-beam duct located at the left of Fig. 2 may be either closed or connected to a vacuum tank. An initial set of experimental runs with a closed ion-beam duct and no ion-beam heating has been made. These initial results indicated that the flow chokes as it enters the exhaust duct, a result that was not expected on the basis of initial one-dimensional, isentropic nozzle-flow predictions.

The initial-experiment configuration was also analyzed numerically, again using hydrogen in place of deuterium. The expansion nozzle and the interaction region were analyzed separately. The nozzle was further subdivided into three parts, each of which was analyzed individually. The velocity-vector plots for the three parts of the nozzle are shown in Fig. 3. (In this figure as well as the remaining figures, the plots are exactly as produced by the computer, with no retouching other than labeling.) The top plot shows the expansion from subsonic to supersonic flow. The second plot describes the further expansion, while the bottom plot shows the jet converging on the centerline of the interaction region. A supersonic start line with a Mach number of approximately 5.8 is obtained for the interaction region calculations by interpolation of the solution for the third section of the nozzle. The stagnation pressure and temperature for these solutions were 1.38×10^7 Pa (2000 psia) and 300°K, respectively.

The solution for the interaction region with a closed ion-beam duct is shown in Fig. 4. The frames from top to bottom are the hydrogen-velocity

vectors and contours of constant hydrogen density, pressure, temperature, and Mach number, respectively. The bottom line of each frame is the centerline of the interaction region. Lines labeled with L represent the low-value contours while those with H are the high-value contours. Looking at the velocity-vector plot, it is seen that the flow velocity is greatly reduced as the flow enters the exhaust duct. In addition, there are large density and pressure increases in this region indicating shock structure. Looking at the Mach number plot, it is seen that both subsonic and supersonic flow exist. From the above observations it appears that the exhaust duct is too small and the flow is, therefore, choked. This initial model was designed using one-dimensional, isentropic theory. The one-dimensional, isentropic Mach number at the entrance of the exhaust duct is 2.7 which would indicate no choking. However, as the flow develops, an oblique shock forms upstream of the exhaust duct at the location where the nozzle jet converges on the interaction-region centerline. This shock causes a loss in total pressure, which results in a Mach number at the exhaust duct that is considerably lower than the one-dimensional, isentropic value. As the flow begins to choke and the resulting shock structure forms at the entrance to the exhaust duct, the upstream oblique shock disappears. These theoretical results agree with the experimentally observed fact that the flow is choked.

The exhaust duct was then enlarged to a diameter of 2 cm and the resulting numerical solution is shown in Fig. 5. The oblique shock that forms at the location where the nozzle jet converges on the interaction-region centerline is clearly visible. In addition, the flow into the exhaust duct appears to be fairly uniform with a Mach number that varies between 2.7 and 3.0. The corresponding one-dimensional, isentropic Mach number is 4.2. The experimental model is presently being modified and data should be forthcoming.

The next configuration to be analyzed is shown in Fig. 6. This configuration is the same as that of Fig. 5, except now the ion-beam duct is open and a pressure of 690 Pa (5 torr) is applied at the end of the duct to simulate the low pressure region of the ion source. Looking at the velocity-vector plot, it is seen that some of the hydrogen flows to the left and enters the ion-beam duct. This hydrogen stream will have to be differentially pumped away in the actual neutron source, and therefore, should be as small as possible. In this case 0.3% of the incoming hydrogen exits into the ion-beam duct. As can be seen from the contour plots, the open ion-beam duct has little effect on the main hydrogen stream.

The final case is shown in Fig. 7 and is the same as that of Fig. 6, except now 100 kw of ion-beam power is deposited. An additional plot showing the contours of constant ion-beam-energy deposition has been included at the bottom of Fig. 7. From this plot, it is seen that some of the ion-beam energy is deposited in the hydrogen that is flowing into the ion-beam duct. This increase in thermal energy of the hydrogen gas also increases the pressure which combined with the low-pressure-boundary condition results in a large pressure gradient in the ion-beam duct. (An improved boundary condition technique is currently being checked out.) This large pressure gradient causes large hydrogen-gas velocities in the ion-beam duct. (The velocity vectors in the interaction region appear as dots, since the vectors are normalized by the largest velocity in the ion-beam duct.) While the hydrogen-gas velocities are large in the ion-beam duct the gas density is low, resulting in escape of only 2.0% of the total hydrogen flow. The temperature plot shows that the hydrogen molecules receive most of the ion-beam energy as they move across the beam and receive little additional energy as they move in the axial direction. In addition, some of the incoming hydrogen forms a layer of cool gas between the hot-interaction zone and the confining walls. From the Mach number plot, it is seen that the main hydrogen stream leaves the exhaust duct without choking.

CONCLUDING REMARKS

A combined experimental and theoretical program for designing the expansion nozzle and interaction region of a supersonic jet neutron source has been discussed. In the future, the theoretical technique will be used to determine improved designs, which then can be further checked experimentally. Future plans call for adding ion-beam heating capability to the experimental program, and including the effects of turbulence, more realistic equations of state, and condensation in the theoretical technique.

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Fig. 1. Schematic of the supersonic jet neutron source.

Fig. 2. Initial-experiment configuration.

Fig. 3. Velocity-vector plots for the three parts of the expansion nozzle.

VELOCITY VECTORS

DENSITY

$$H/L = 8.3$$

PRESSURE

$$H/L = 8.9$$

TEMPERATURE

$$H/L = 6.1$$

MACH NUMBER

$$L = 0.6, H = 5.2$$

Fig. 4. Interaction region solution with closed ion-beam duct and 1 cm diameter exhaust duct.

VELOCITY VECTORS

$$H/L = 6.1$$

DENSITY

$$H/L = 7.6$$

PRESSURE

$$H/L = 4.4$$

TEMPERATURE

$$L = 0.6, H = 5.2$$

MACH NUMBER

Fig. 5. Interaction region solution with closed ion-beam duct and 2 cm diameter exhaust duct.

VELOCITY VECTORS

$H/L = 8.1$

DENSITY

$H/L = 8.7$

PRESSURE

$H/L = 2.8$

TEMPERATURE

$L = 0.6, H = 5.2$

MACH NUMBER

Fig. 6. Interaction region solution with open ion-beam duct and 2 cm exhaust duct.

VELOCITY VECTORS

DENSITY

$H/L = 9.0$

PRESSURE

$H/L = 8.7$

TEMPERATURE

$H/L = 8.2$

MACH NUMBER

$L = 1.5, H = 13.1$

ENERGY DEPOSITION

$H/L = 9.0$

Fig. 7. Interaction region solution with open ion-beam duct, 2 cm exhaust duct, and 100 kw of ion-beam power.