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SUMMARY OF RECENT GASEOUS REACTOR FLUID MECHANICS EXPERIMENTS

by Robert G. Ragsdale and Chester D. Lanzo

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Cleveland, Ohio

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ABSTRACT

Three recent gaseous-nuclear rocket related fluid mechanics experiments have shown ways of reducing the mixing of two coflowing streams. In a rocket engine, such a reduction would mean less uranium loss or a lower pressure reactor. Two of the experiments were conducted with room temperature gases. The third experiment used induction heating to simulate fission heating. In these experiments, no major flow recirculation and mixing was observed, as contrasted with previous studies.

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SUMMARY

The results described in this report indicate that it may be possible to reduce the uranium loss rate by a factor of 2 to 10 below that indicated by previous experiments. One of the experiments employed induction heating to simulate fission heating. A central stream of argon simulated the uranium of an engine, and hydrogen was flowed around it. Concentration measurements made with a probe show that heat addition eliminated a recirculation flow pattern that was present with cold flow. The new flow pattern had much less mixing or interaction between the two streams. The second experiment described used straight coaxial flow of two gas streams through a cylindrical test section. These tests used iodine-colored air to simulate the central uranium stream, and clear air to simulate the outer hydrogen propellant. These tests were conducted at high, engine simulating Reynolds numbers. Flow visualization has disclosed that injection of the two gas streams through a very porous, foam-like material eliminates a recirculation cell that previously occurred. The third experiment discussed examined the flow characteristics of a curved, porous wall cavity. In a two-dimensional mockup of this concept, clear, propellant-simulating air was injected through the porous wall, and smoky, uranium-simulating air was injected through a shower-head injector at one end of the cavity. Both gases exited through a nozzle opening that opposed the fuel injection port. These tests show the existence of a large, relatively stagnant fuel region in the center of the cavity. Each of the experiments has disclosed a favorable flow characteristic.

INTRODUCTION

The primary function of a gaseous-fueled nuclear rocket engine would be to produce a thrust that is at least equal to its own weight, and at a specific impulse of 1500 seconds or greater. Research over the past 12 years has shown that such engines have the undesirable features of high pressure, large weights, and nonnegligible uranium loss rates. The question of whether the good outweighs the bad is presently unresolved.

The uranium loss can be conceptually eliminated by encapsulating the fissioning, gaseous uranium within a transparent tube that transmits the energy generated through as thermal radiation to the hydrogen propellant flowing around the tube. Such a "closed-cycle" concept is under investigation, supported by the AEC/NASA Space Nuclear Propulsion Office (ref. 1). The survival of the transparent material in the cavity environment is the key to success of this concept. References 2 to 5 provide summaries of this and other gaseous reactor concepts and related research studies.

In this report, some recent experiments that have been performed on geometries that would be used in an open-cycle engine are described. In such an engine the gaseous fuel and the surrounding hydrogen are in direct contact. This feature removes the requirement of a solid transparent material within the cavity. It also allows some of the uranium to be carried out of the engine by the hydrogen propellant. It has been shown in reference 5 that approximately 20 percent of the cavity volume must be occupied by gaseous uranium fuel in order to achieve criticality at a reactor pressure of less than 1000 atmospheres. Attainment of this fuel volume fraction at an acceptable uranium loss rate is the key to success of this concept. The fluid mechanics research on open-cycle concepts is aimed at reducing fuel loss without reducing the amount of fuel within the cavity. This generally involves doing things that change the basic flow pattern of the gases through the cavity.

The experiments described in this report were aimed at reducing the amount of mixing, and therefore the resulting fuel loss, between the two gas streams within the cavity. Two of these experiments were done at room temperature. The third experiment described has internal heat generation in the fuel simulating gas (ref. 6). This is achieved by using high frequency, induction heating. Induction heating simulation of gaseous fission is also being used in closed-cycle studies (ref. 1). Each of the three experiments described herein has shown a way to reduce the mixing of the two gas streams as they flow through the cavity. By examining these results, one would hope to find a way to combine them into one test that would retain the advantages of each of the individual configurations.

COAXIAL FLOW EXPERIMENT

The experiment described herein was done as a part of the gaseous reactor work being supported under NAS w-847. The open-cycle work under discussion has been done on a cylindrical geometry through which the fuel and propellant flow coaxially. This work has grown from interest in a coaxial flow concept that has been under investigation at the Lewis Research Center for a number of years. A detailed description of these coaxial flow experiments can be obtained in NASA CR-1190, which is reference 7 of this report. The work has been quite extensive, and has included many more variations of geometry and flow conditions than will be covered in this report. The general purpose of the work was to determine the variation of fuel volume fraction with propellant-to-fuel flow rate ratio for a large number of geometrical configurations, and at Reynolds numbers such as would occur in an engine.

Figure 1 shows a sketch of the essential features of the experimental apparatus. A central jet of low velocity air ("fuel") is injected into a surrounding high velocity stream of air ("propellant"). The two gases flow through the cylindrical cavity and exhaust through a subsonic nozzle that is located approximately one cavity diameter downstream. The central air stream contains iodine to give it a red color so that the flow pattern can be seen. The cavity channel is 10 inches (25.4 cm) in diameter and the fuel jet is 5 inches (12.7 cm) in diameter.

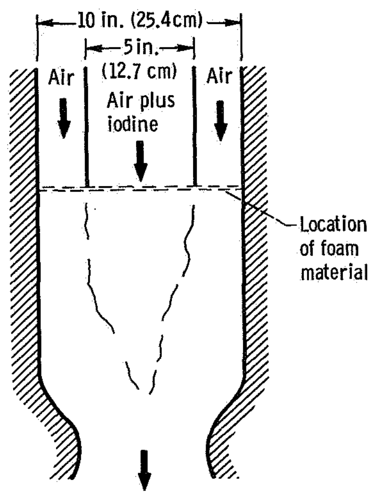

Figure 1. - High Reynolds number coaxial flow experiment.

The experimental studies included variations of the major geometry factors of fuel injection radius, the cavity length, and the nozzle radius. The effect of density differences was studied by using two different Freon-type gases as the fuel in addition to using air. The two flow parameters studied were the jet Reynolds number (it was varied from 2000 to 120 000), and the ratio of the propellant to the fuel flow rates. This latter parameter is the one of most interest, and it was varied from 3 to 1 up to 100 to 1. Quantitative measurements of fuel concentration distributions were obtained with a light absorption technique.

Qualitatively, the flow field was studied by taking still and motion pictures of the flow through a transparent test section. A photograph of the apparatus in this configuration is shown in figure 2. The most important result of the flow visualization part of the

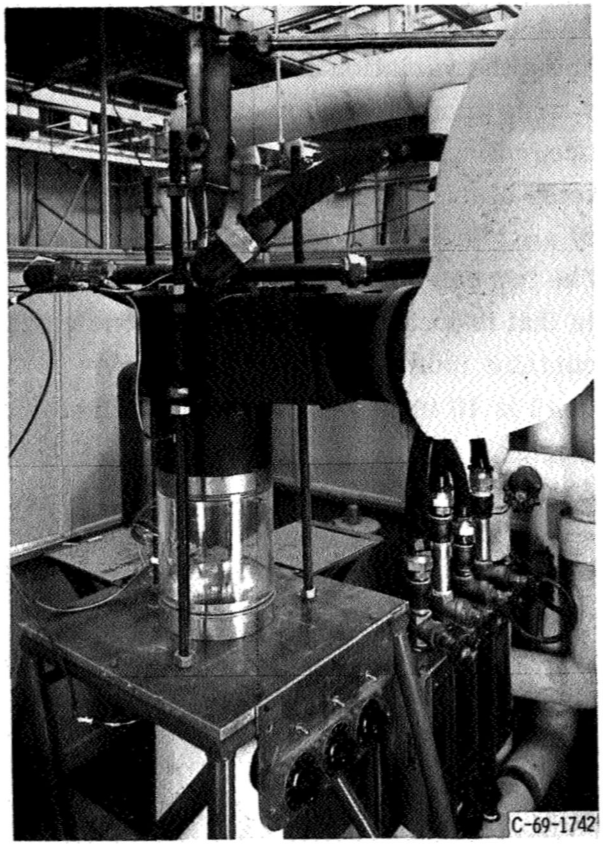

Figure 2. - Coaxial flow experiment.

study was the identification of a "recirculation cell" or reverse gas flow pattern that forms in the cavity and virtually fills it as the ratio of propellant to fuel flow rate is increased. Such a recirculation pattern is undesirable because it enhances mixing and also because it could lead to dynamic control difficulties if it were to occur in an actual engine.

At propellant to fuel mass flow rate ratios of 30 or less the recirculation cell was not present. This is shown in figure 3. The mass flow ratio of 30 to 1 corresponds to a velocity ratio of outer to inner stream of about 10 to 1. As the flow rate of the inner fuel stream was decreased the recirculation pattern began to develop. That is, reverse flow occurred along the cavity centerline near the exit end. As the fuel flow was further reduced this back-flow pattern increased. At a mass flow ratio of 50 to 1 (velocity ratio of 17 to 1), the recirculating flow pattern essentially filled the entire cavity. This is shown in figure 4. The camera and lighting conditions were not necessarily the same for the two photos, so that the comparison of the two flows is only qualitative. The main point is that an undesirable recirculating flow pattern developed at mass flow ratios above about 30 to 1.

Subsequent experiments were carried out to determine the effect on this flow pattern

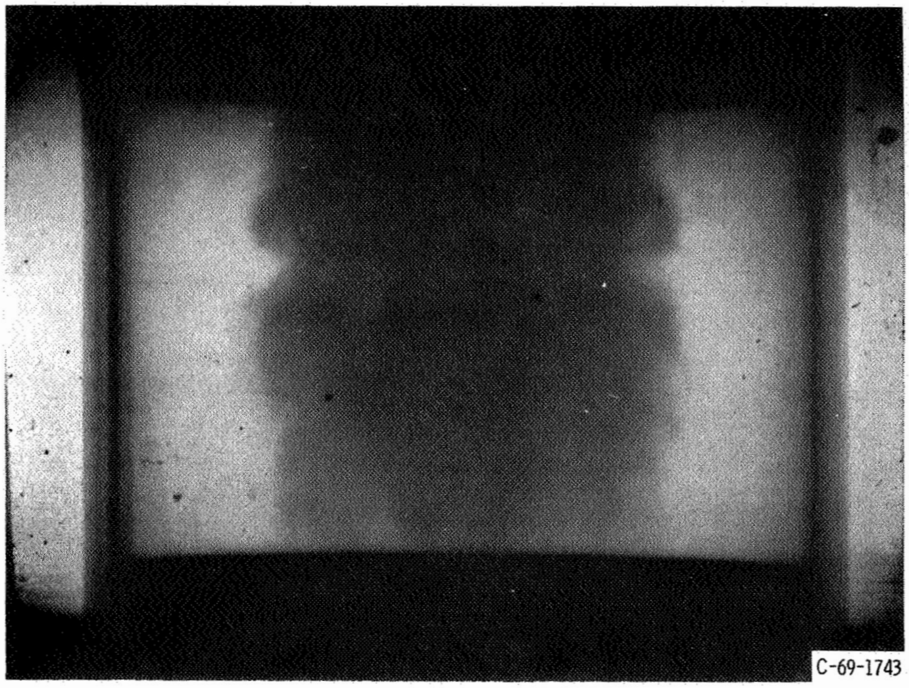

Figure 3. - Coaxial flow at a mass flow ratio of 30; no foam material.

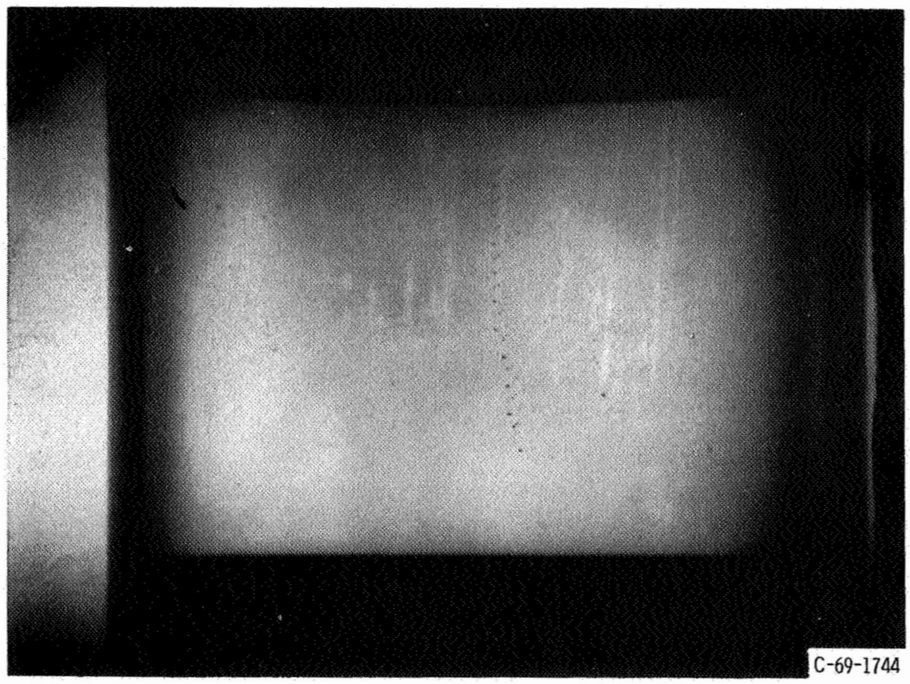

Figure 4. - Coaxial flow at a mass flow ratio of 50; no foam material.

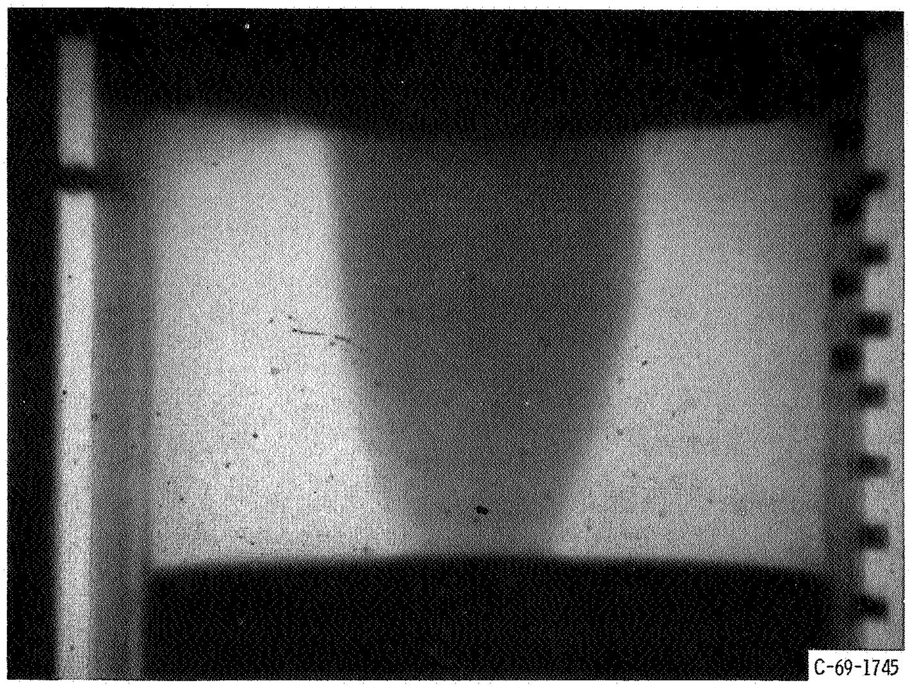

Figure 5. - Coaxial flow at a mass flow ratio of 30; with foam material present.

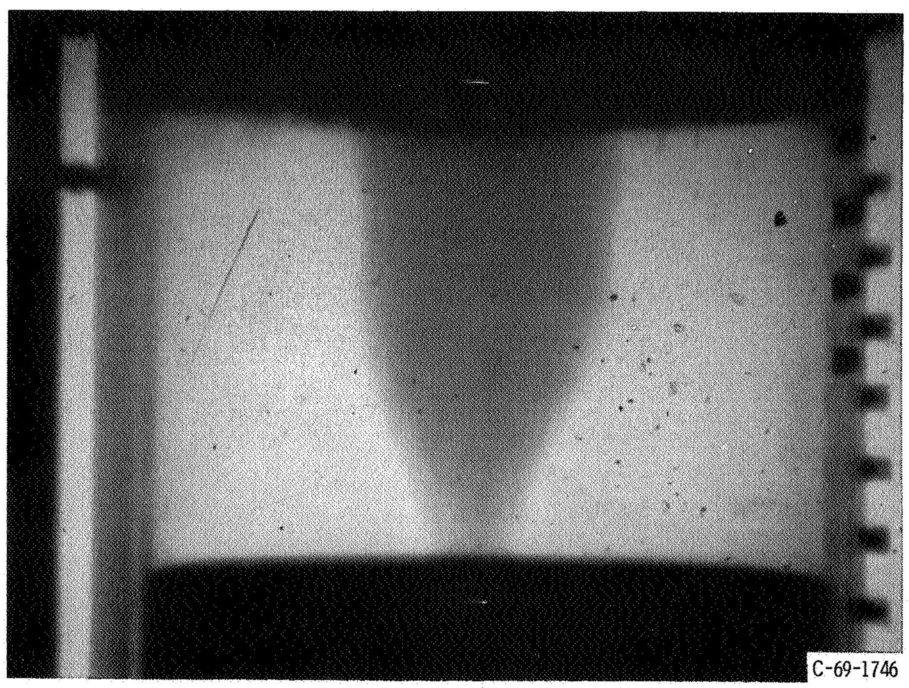

Figure 6. - Coaxial flow at a mass flow ratio of 130; with foam material present.

of the inlet velocity profiles and turbulence levels. In order to change these quantities, a porous, foamy material was placed across the entire inlet plane. Both the outer and inner flows were injected through this material. The foam material was quite similar to the light, porous media commonly used in home humidifiers and air conditioners. In the experiment, the foam was 1/2 inch (1.25 cm) thick.

The presence of the foam had a dramatic effect on the character of the cavity flow. At the low mass flow ratio of 30 to 1, the flow appearance changed from the rough, "turbulent" structure shown in figure 3 to a smooth "laminar" structure. This is shown in figure 5. As the mass flow ratio was increased, the general appearance of the flow remained the same, though the diameter decreased somewhat. Figure 6 shows the flow at a mass flow ratio of 130 to 1. This is considerably beyond the flow rate ratio at which recirculation occurred (50 to 1, see fig. 4) in the previous experiments without the foam present. There is no recirculating reverse flow at a mass flow ratio of 130 to 1. Similar photographs have been obtained for mass flow rate ratios up to 300 to 1. They show that no recirculation flow develops. As the flow rate ratio is increased, the center fuel region continues to look much like that shown in figure 6, except that the diameter shows a further moderate decrease.

Experiments are continuing to obtain quantitative information about this new flow pattern. Flows with density differences are being studied. The radius of the fuel injection pipe is being increased so as to enlarge the fuel region within the cavity. Previous work has shown there is some "best" fuel radius, and this will be determined for the new flow.

The main conclusion to date from these recent results is that a new, more desirable flow pattern has been obtained.

CURVED POROUS WALL EXPERIMENT

Although it is more convenient for analysis and for basic coaxial flow experiments, a simple cylindrical geometry would probably not be practical for an actual engine configuration. Because of such things as wall cooling requirements and pressure shell design, a spherical design is more likely. This train of thought leads to the notion that all of the propellant would not be injected in a coaxial stream immediately adjacent to the fuel injection location. More likely, the propellant would be introduced all along the cavity wall, with some distribution dictated by a trade-off between wall cooling requirements and the effects of such injection of the flow pattern within the cavity.

An experiment has been carried out at Lewis Research Center on such a flow. The purpose was to determine the general character of the flow, and to see if it appears favorable or unfavorable for gaseous reactor application. The study was conducted at room temperature and atmospheric pressure. Air was used to simulate the propellant.

Air with smoke added to make it visible was used to simulate the gaseous uranium fuel. A two-dimensional mockup of the spherical geometry was used so that the flow pattern could be visually observed through flat transparent sides. A photograph of the experimental setup is shown in figure 7. The diameter of the cavity is 9 inches (23 cm) and the two parallel flat sides are 6 inches (15.2 cm) apart.

The propellant-simulating clear air was introduced through the curved porous side walls. The side walls are constructed of brass sheet metal that had holes through it. The metal was 0.025 inch (0.064 cm) thick. The holes were about 0.010 inch (0.025 cm) in diameter. The overall porosity, or open area fraction, of the wall material was about 0.25. Velocity measurements over the inner surface of the curved wall indicated that the incoming propellant flow was quite uniform from the inlet end to the outlet end.

A shower-head type fuel injector was used to introduce the smoky air into the cavity. The general idea behind this geometry is that it may somewhat represent the expanding flow that would occur in an engine due to heat generation in the uranium as it enters the cavity. The shower-head surface is constructed of the same material as is the walls. The fuel gas is injected at one end of the cavity, and the propellant is introduced all along the curved side walls. Both gases then exit through a subsonic nozzle at the end opposing the fuel entrance. This can be seen in figure 7.

These experiments have shown that there is a relatively large central volume into which the fuel expands. The average dwell time of the fuel in this region is 30 to 40 times the dwell time of the propellant in the outer region. The fuel region is from

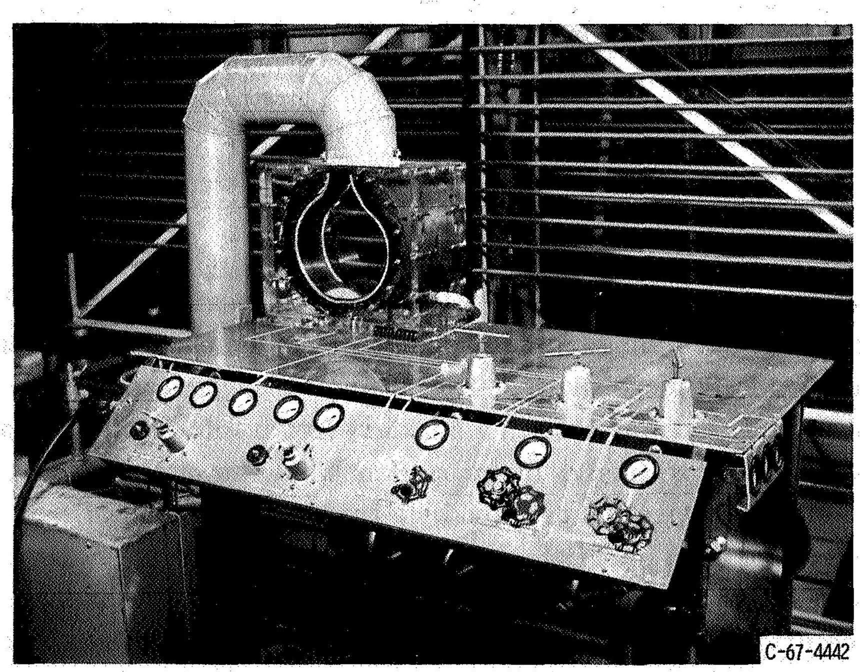

Figure 7. - Curved porous wall flow experiment.

one-fourth to one-half of the cavity volume. This fuel volume fraction depends on the propellant to fuel flow rate ratio. As the propellant flow is increased, relative to that of the fuel, the size of the fuel volume diminishes, as one might expect.

The variation of fuel volume fraction with flow rate ratio is a favorable one, however. That is, the fuel volume decreases only as the square root of the increasing flow rate ratio. The fuel volume within the test section cavity was obtained from photographs of the flow. Figure 8 displays the flow field for a propellant to fuel flow rate ratio of 100 to 1. This photograph is a time average (about a 13 sec exposure time) picture. Instantaneous pictures show much more structure in the flow. The time average photograph was taken because it provides smoother concentration profiles, which are then easier to integrate in order to obtain fuel volumes. The photographic negative was used to produce concentration profiles through the use of a microdensitometer. The densitometer traces actually measure the film density, which is taken to be proportional to the amount of smoke, or "fuel" that was between the back lighting and the camera. This assumes many things such as uniform light intensity over the flow field, linear film response, and an exponential variation of light absorption with smoke density. None of these assumptions are likely to introduce any significant errors.

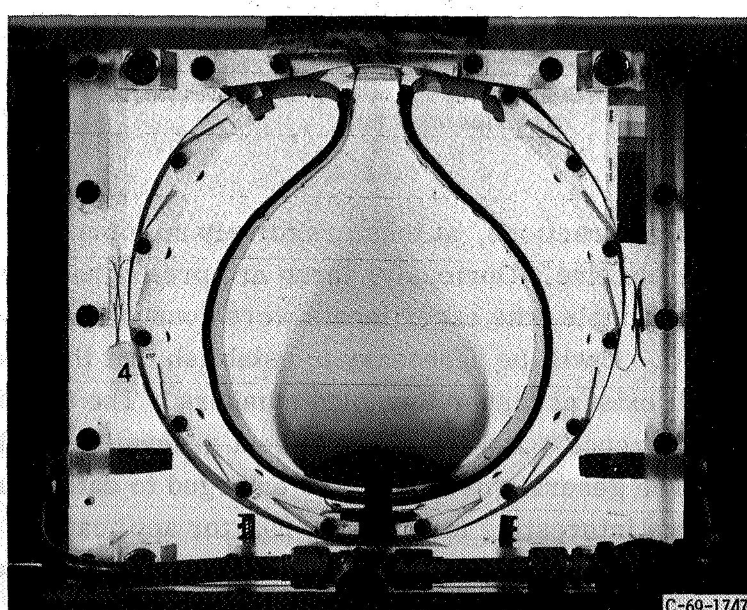

Figure 8. - Flow pattern at a mass flow ratio of 100.

The fuel distribution within the cavity is shown in figure 9 for a flow rate ratio of 100 to 1. The concentration is a relative one; it is normalized to the value at the fuel injector face. Thus, 1.0 represents pure fuel, and 0.5 represents a weight fraction of half fuel and half propellant. Figure 9 shows that the fuel concentration is pretty uniform radially, but that it falls off fairly rapidly in the axial direction. At the center of the cavity, for example, the fuel concentration is about 20 percent of the inlet value. The remaining 80 percent is propellant. Similar profiles were obtained for mass flow ratios of 25, 50, and 75. Fuel volume fraction varied from 0.5 to 0.3 as the mass flow ratio varied from 25 to 1 up to 100 to 1, respectively.

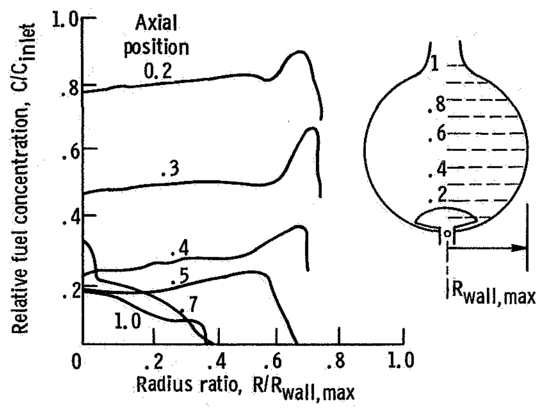

Figure 9. - Fuel distribution in curved porous wall rig at mass flow ratio of 100.

These high fuel volume fractions, at these relatively high mass flow ratios, make this flow pattern quite attractive. Obviously, these are preliminary tests and additional work is required. For example, the experiments were conducted at the relatively low Reynolds number of 1100. It will be necessary to establish that the present flow pattern, or one just as good, will exist at higher Reynolds numbers. The effect of using two different gases (density difference), and the effect of heat generation on the flow pattern must also be studied. The general result that has emerged to date from these tests is that the flow pattern looks interesting for gaseous reactor application, and that for the air-air simulation, has provided the best fuel volume fractions that have been reported.

INDUCTION HEATED FLOW EXPERIMENT

The third experiment described herein utilized induction heating or a central "fuel" gas to simulate the fission heating that would take place in an engine. These two processes are similar in that they are both a form of internal heat generation. The experiments were carried out for Lewis Research Center under NAS-3-9375 and NAS 3-11487. The portion of this work covered here involved measurement of concentration profiles inside the induction "torch."

Figure 10 shows a sketch of the experimental apparatus. A central stream of argon (fuel) was injected into a surrounding flow of air (propellant). The two gases flowed within a 3-inch- (7.6-cm-) diameter cylinder. The argon was injected through a 2-inch- (5.1-cm-) diameter entrance tube. The flow channel, or torch, was located within a surrounding water-cooled copper tube coil. High frequency alternating current was passed through this copper coil. The current in the coil "coupled" to the argon flow. The argon was then heated in the same way a steel load is inductively heated when it is placed within an induction coil. Of course, the argon must be ionized in order that the magnetic field can couple to it. The initial ionization is achieved by striking a direct current arc within the torch, once gas flow is established. As soon as the high frequency (rf) field couples to the gas, it is self-maintaining and the direct current arc is extinguished.

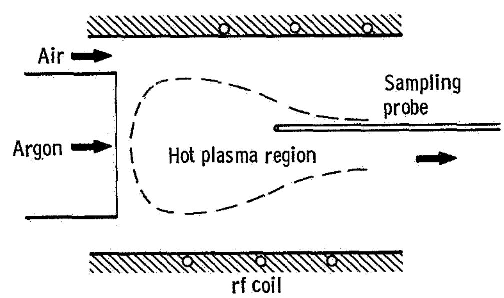

Figure 10. - Induction heated flow experiment.

The argon concentration distribution within the cylindrical cavity was obtained by sampling with a probe. The probe was inserted through the exhaust end of the cavity, as shown in figure 10. The probe was water cooled so as to withstand the high temperature (about 20 000° R; 11 000 K) plasma environment. A sample of the gas at a given location was withdrawn through the probe and passed through a gas chromatograph to determine relative composition. Figure 11 shows the experiment in operation.

Concentration profiles were first obtained for cold flow, that is, the torch was not ignited. Following this, the torch was ignited, and the measurements were repeated. The results obtained are quite interesting. Figure 12 shows a typical set of measurements. The profiles for the cold flow are shown in the lower half of the figure, and the profiles for the heated flow are in the upper half. The profiles for the cold flow show the same kind of recirculation pattern that was observed in the coaxial flow experiment first described in this report. The outer air has penetrated in to the argon jet center at

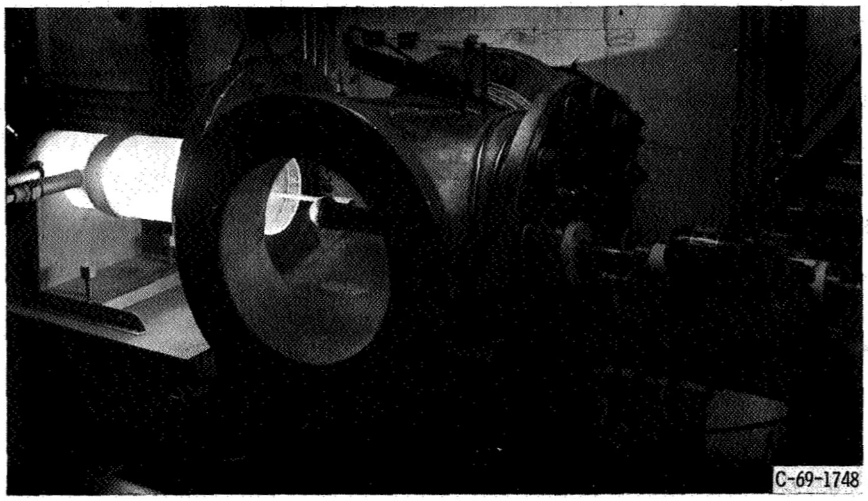

Figure 11. - Hot flow experiment in operation.

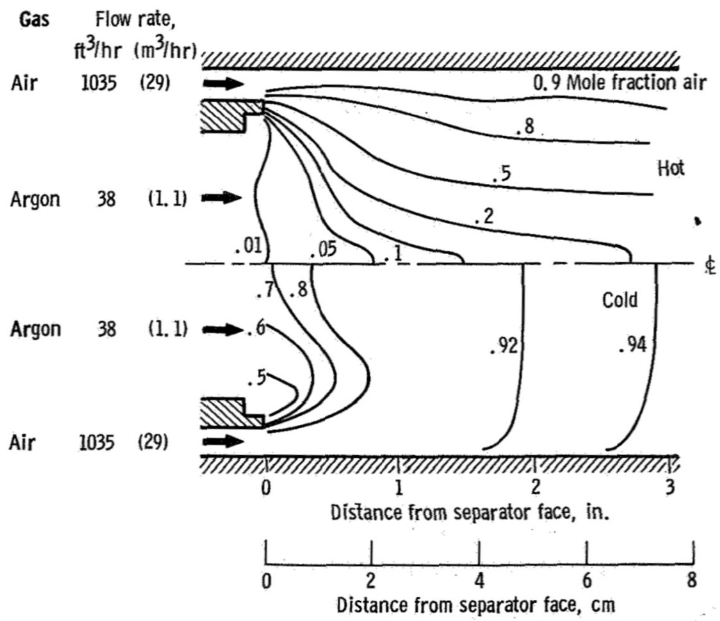

Figure 12. - Comparison of hot and cold coaxial flow, for a mass flow ratio of 20 to 1.

the injection plane. The fact that the air concentration is greater at the centerline than it is at some intermediate radial location indicates that air from farther on downstream has recirculated back toward the jet injection plane.

The concentration profiles for the hot flow are shown in the upper half of figure 12. They show no recirculation of the flow. The flow rates of the air are the same for the two cases. The only difference is that there is internal heat generation in one case and not in the other. Virtually identical results have been obtained by using hydrogen instead of air for the outer gas. Recirculation was observed in the cold flow, and was not found when heat was added. The hydrogen tests were conducted at a mass flow ratio of about 2 to 1, which gave an initial velocity ratio of 40 to 1. The initial velocity ratio for the run shown in figure 12 was 33 to 1.

The general indication of these experiments is that the presence of the heat generation has greatly reduced the interaction of the two streams. Thus, it appears that the hot central plasma core is not easily penetrated by the cold outer flow. This obviously has favorable implications for a gaseous reactor, where the central uranium ball is at a temperature of 50 000° to 100 000° R (90 000 to 180 000 K). It is tempting to postulate models to account for this effect. But it is likely that the process is complicated enough that more experimental information will be needed to really explain the phenomenon. The importance of the work to date has been simply to disclose the fact that the mixing is greatly reduced when heat is added to the central stream.

CONCLUDING REMARKS

The three experiments described herein were all conducted during the past year. Thus, there has been no opportunity as yet to allow any crossflow of information from one of them to the others. And it is obvious that this is the way to go. Each of the experiments have indicated a new and favorable feature that should be incorporated into future gas-core work. The findings are all relatively new, and so they are not completely understood. Certainly more work will be necessary to explain the experimental observations. But more important than the ensuing explanations are the observations themselves. The general feature of all three experiments is that the mixing rates encountered in previous experiments have been reduced. If similar improvements can be realized under engine operating conditions, the uranium loss rate and/or the engine pressure would be less than has been anticipated based on earlier results.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 7, 1969,
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