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Fifth Semi-Annual Report

A Fundamental and Feasibility Study of Ring-Vortex Gaseous-Core Cavity Reactor

From February 1, to July 31, 1966

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I. Introduction

This is the fifth semi-annual report (February 1 - July 31, 1966). During the last two and one-half years, from February 1, 1964, to July 31, 1966, research work has been carried out in the Department of Space Science and Applied Physics, Catholic University of America on the feasibility study of gaseous core cavity reactor under the Grant NsG 586 which mainly concerns the fluid mechanics in the reactor.

Three types of reactor models are studied: (1) cylindrical geometry, (2) toroidal geometry and (3) two dimensional improvement on Lewis Coaxial Core Reactor. A great deal of progress in understanding the flow pattern in the cylindrical geometry is obtained. A remarkable improvement in the containment of the toroidal geometry is also achieved.

II. Experimental Work

(A) Cylindrical Model

(a) End Wall Geometry on Flow Pattern

It is well known that the flow pattern in the cavity of cylindrical geometry is extremely complex and difficult to evaluate theoretically and experimentally. Because of the three dimensional rotational flow, any instrument which, no matter how small, measures some flow property such as total pressure inside the cavity will interfere with its own wake and violently change the flow pattern. The measurement may become doubtful if not useless. For this reason, no one available flow pattern is known in the open literature.

(1) End Wall Configuration

The first question is: What shape of end wall will give the least loss of secondary flow? The answer is not fully clear although some partial answer is obtained as follows. Square Step End Walls - The square step end walls of equal diameters are definitely promising in reducing secondary flow loss. Let us consider the evenly spaced side wall jets to be small in diameter and laminar in flow. The outlet is located on one bottom end at center of the step end wall. In this case, the flow pattern in the side view is shown in Fig. 1 and is obtained through interpretation from many photographs and observations with injection of flourescent dye solution into the water flow in the cylindrical cavity. The distribution of circulation of Γ along the cylinder axis is also indicated. Fig. 2 shows the distributions of velocity components, U (radial), V (tangential) and W (axial), at three sections, 1, 2, and 3. These distributions are interpreted from the dye qualitatively and are not accurate enough but consistent with the flow pattern observed. The static pressures at sections 0 and 4 are also indicated. The detail description will not be given here and will be included in a report entitled, "End Wall Effect on Flow Pattern of Cylindrical Cavity Reactor Model," which is in progress and will be published later.

The apparent advantages of the square step end walls are the following:

(i) Bottom square step end (outlet side) cut-off the end second flow so much that leak is extremely small and that the boundary secondary flow becomes extremely thin.

(ii) A recirculation zone is formed between the zone of center fast moving downward flow and the upward wall flow zone. The former may be called core flow zone and the latter upward flow zone. The total discharge of core flow is nearly constant in amount and in size at any section below the top tip of the recirculation zone. In this zone of recirculation, the flow is nearly two-dimensional vortex motion while both U and W are extremely small. Therefore, the trapped water of flourescent dye can recirculate around, diffuse very slowly and last a very long time. The opposite moving fluid on both sides of the recirculation zone will not encounter each other and the velocity gradient is very small inside the recirculation zone. The tangential velocity V in the recirculation zone varies nearly with $\frac{1}{r}$ and is nearly potential. Thus, the viscous loss can be neglected. Maximum tangential velocity likely occurs in this zone and the strong centrifugal force can trap heavy fluid. Therefore good containment of heavy fluid can be obtained. In this zone, the invicid flow theory can be applied.

(iii) In the upward flow zone, all the incoming fluid flows spirally upward and inward along helixical path and passes around the top of the said recirculation zone and concentrates radially inward to join the downward core flow.

(iv) The flow field in cylindrical cavity is thus divided into five zones: (a) core flow zone of nearly constant flow and diameter rate, (b) recirculation zone mainly a region of a potential vortex, (c) upward flow zone, rising spiral flow which increases nearly linearly with height frombottom wall, (d) top secondary flow zone which is a thicker layer and (e) bottom secondary flow zone which is extremely thin layer. Fig. 2 shows clearly the zones of (a), (b) and (c).

(v) Gap between each end step and side cylindrical wall acts as a cushion to reduce the shear stress and allows the decay of circulation very slowly. This reduces the viscous dissipation. The centrifugal force of reasonably large rotational velocity in the gap can balance against the radial pressure gradient, and is favorable to reduce the secondary flow in the gap. The static pressure distributions both near the top and bottom are also shown in Fig. 2.

(vi) Any transient change in the flow rate in the zone of recirculation will change the size of the zone immediately. If the flow rate increases suddenly, the recirculation zone moves inward into the core flow, and the trapped flourescent fluid is quickly washed away by the core flow. If the flow rate decreases, the recirculation zone will expand beyond the step and again the trapped flourescent fluid is washed away by the upward outer flow. Thus, the trapped dye solution in the recirculation zone loses very quickly.

Curved Step - Seems to increase secondary flow loss at the top and to increase the loss of the core flow.

Tapered Outward Steps - Produced ~~way~~ WAVY transient boundary interface between the recirculation zone and outer upward flow zone. Therefore more diffusion losses occur. It is expected to be poor in containment of heavy fluid.

Flat Wall With No Steps - This arrangement seems to produce more complex flow pattern than the geometry with square steps. Secondary flows both in the top and bottom layer regions are stronger and loss is more. The recirculation zone is always small and the peak of maximum tangential velocity is sharper, and diffusion is strong. The containment is definitely inferior to that of the square step case.

(b) Heavy and Light Gas Mixture

The model is operated with a fixed ratio of heavy and light gas mixture (Freon and helium) under choking condition at the outlet throat. It is planned to measure the composition of gas mixture continously with time at the throat at outlet which is in high vacuum. After running for a sufficiently long time until the exhaust mixture approaches closely to the fixed inlet mixture, the cylindrical cavity is stopped and isolated and mixture composition in the cavity is determined. The work is in progress and will be reported later.

(B) Toroidal Geometry

The great advantage of toroidal geometry is the fluid vortex ring which has no open ends. Therefore, the secondary flow loss can be eliminated. With centrifugal effect, in order to keep the heavy gas or particles of the inner diameter of the ring as far from the outlet mouth as possible, strong rotation along the ring direction is essential. Thus, the fluid particle moves helexically along the ring. Now near the outlet, the pressure is very low and the flow direction is reversed and the flow will expand and be choked there. The rotating lighter gas will expand suddenly and will be able to turn around the sharp corner to escape through the nozzle to vacuum. This phenomenon is somewhat similar to Prandtl-Meyer flow but much more complex because of the three-dimensional rotational flow. The heavy gas being of higher density will expand much slower in response to pressure than the lighter one. It is expected that the heavy gas being of higher momentum moves fast but cannot turn so large an angle of 90° as the light one. Therefore, the heavy gas cannot expand far enough to enter the nozzle throat to escape, but strikes on the surface of the sharp cone of the center of the cavity bottom tangentially and remains to recirculate in the cavity. Let us consider the operating cycle of the propellant. The cold light gas which is injected from the wall into the cavity, diffused into heavy fuel gas, absorbs the heat essentially through radiation and rotates with the ring vortex flow and escapes by turning around a sharp corner into the vacuum of outlet nozzle. Because of the low pressure near the nozzle throat, the light gas will accelerate more than the heavy one and more easily turns around the sharp corner. At the inner radius of the ring cavity, the horizontal tangential velocity component is the highest and the outward centrifugal force is highest. Therefore, heavy gas can separate from the wall before reaching the mouth of the nozzle. This desirable phenomena can happen only when inward centrifugal force of the vertical tangential component, plus the pressure gradient, is much smaller than the outward centrifugal force due to horizontal tangential velocity component. There are many advantages of the toroidal geometry:

a) No secondary flow loss is possible because of no ends.

b) The horizontal tangential velocity component and the vertical tangential velocity component can be controlled separately to meet the flexibility of reactor loading.

c) The suction at the nozzle mouth can accelerate the gas flow to nearly sonic speed within the cavity. Higher outward centrifugal force can separate the heavy gas better if the horizontal tangential velocity is high enough.

d) The reverse flow nozzle can prevent the heavy gas from turning more than 90° and from escaping.

e) Pressure diffusion is a function of temperature. The lower temperature associated with suction near the outlet will reduce the pressure diffusion also. This is another favorable point.

So far the toroidal model is operated with (a) water and glass beads, (b) gas and flourescent solid particles of sawdust. The containment is excellent. With the available experimental setup, the water speed is too low to give good containment with oil droplets or or gas mixtures. Also the flow is too turbulent and the oil droplets are too fine. A great deal of study and refinement is needed before the flow pattern and pressure distribution can be interpreted qualitatively with confidence.

(C) Two-Dimensional Improvement on Lewis Coaxial Core Reactor

A two-dimensional model with recirculation cavity of gaseous nuclear fuel is developed. After many adjustments and improvements, the model can keep the fuel much longer than the previous model. However, the work is in the preliminary stage and further study should be done.

III. Theoretical Work

(A) Cylindrical Geometry

(a) Approximate Analysis

Owing to complicated geometry of the square step cylindrical model, exact theoretical analysis is not possible for the immediate future. Some approximate analysis is carried out with given boundary conditions such as

(1) On the cylindrical wall with assuming axial symmetry $W_o = 0$, U_o and V_o are given constants.

(2) On top end $W = 0$.

On lower end $W = W_o(r)$.

(3) Pressure on both ends are approximately equal. Some analytic solutions are obtained if $W = \quad Z \, \overline{W}(r)$.

A number of interesting properties are obtained. However, from the recent experimental evidence that W in the core flow zone is likely a strong function of r only and nearly independent of Z. W in the outer upward flow zone is expected probably of the form

$$W \qquad \left(1 - \frac{Z}{L}\right) \frac{1}{r} \; \overline{W}(r)$$

We are planning to calculate with the above new assumption. In the recirculation zone $W = 0$ and $U = 0$ is a reasonable assumption. The work is in progress.

(b) Numerical Analysis of a Confined Vortex

An exact analytic numerical program with computer is in process. A numerical scheme using full Navier-Stokes equations, for the vortex flow in a closed container, is being developed. A simpler flow model is used in the first stage of the numerical integration. The fluid is confined between a rotating top hood and a stationary bottom plate, with possible inflow and outflow. For Reynolds number smaller or equal to 100, the convergence of the numerical iteration is quite good, and the flow is stable. When the Reynolds number increases, the flow in the end wall boundary layer intensifies, and the convergence of the numerical iteration becomes very slow. Physically, it is to be expected that the flow becomes unstable and unsteady when the Reynolds number becomes large. Hence, the problem has to be solved as an initial value problem. The corresponding numerical scheme is being developed. The case of $Re = 1000$ has been integrated quite successfully. The result shows the development of the end wall boundary layer flow and the viscous vortex core.

(B) Toroidal Geometry

Some theoretical study on toroidal geometry is just started. Because of the complication of geometry, the basic Navier-Stokes equation is now in derivation to this coordination.

(C) Radiation and Mass Diffusion

1. Binary Gas Diffusion (T. Kao)

The central problem involves the flow of a binary gas mixture under a body force which is either external or which is provided by a swirling motion of the whole fluid. The heavier maximum species has a number density (number of molecules per unit mass of mixture) which is much smaller than the lighter parent fluid. The transport coefficients of such gas mixtures at high temperatures are governed primarily by molecular collisions and the flow is usually at sufficiently low Reynolds number that turbulent effects are minimized.

The governing equations for the study of the dynamics of a binary gas mixture under isothermal conditions are:

Motion: $$\rho\left(\frac{\partial\vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right) = -\nabla p + \vec{F} + \mu\nabla^2\vec{u},$$

Continuity: $$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0,$$

Continuity of heavy species: $$\frac{\partial c}{\partial t} + (\vec{u}\cdot\nabla)c = -\frac{1}{\rho}\nabla\cdot\vec{i},$$

i = mass flux of heavier species and

$$\vec{i} = -\rho D\left[\nabla c + k_p\frac{\nabla p}{p}\right],$$

The equation of state is $$p = \rho\left[\frac{1-c}{m_2} + \frac{c}{m_1}\right]RT,$$

k_p can be calculated for perfect gas mixtures from the equation of state and the chemical potentials and is $$k_p = (m_2 - m_1)c(1-c)\left[\frac{1-c}{m_2} + \frac{c}{m_1}\right],$$

The above system is then the complete set of equations for solving $\rho, \vec{u}, p, c$ from some initially given conditions.

Some useful information can be immediately obtained by dimensional considerations. In most problems of practical interest there is a velocity of the through flow, U, for the system. There are thus the following time scales

$t_D = \frac{L^2}{D}$ diffusion time

$t_g = \sqrt{\frac{l}{g}}$ free fall time scale due to body force

or $t_\Omega = \frac{1}{\Omega}$ time of one revolution in the centrifugal case

$\bar{t} = \frac{l}{U}$ through flow time scale

and the non-dimensional parameter of the problem is the Péclet number, Reynolds number, ratio of the masses, and the Mach number. In the case where the body force is supplied by the swirl itself, the non-dimensional coefficient for the pressure diffusion term is $\propto \left(\frac{m_1}{m_2}\right)M^2$ where M is the Mach number based on the maximum swirl velocity over the sonic velocity in the parent gas. For centrifuge separation to occur at all $\underline{\left(\frac{m_1}{m_2}\right)M^2}$ must be at least of $\underline{0\ (1)}$.

In order to make meaningful estimates of retention, it is necessary to know the time for which separation is achieved compared with the time for through flow. This time must lie between t_g and t_d but cannot be estimated à priori unless we solve the problem. Thus it is important to consider transient problem in the establishment of concentration profiles. This problem will be investigated in the near future.

The evolution of the concentration profile of the heavier species in the flow of a binary fluid mixture was studied. An incompressible theory was presented. The results were published in a paper entitled "Establishment of Concentration Profile for the Flow of a Binary Fluid Mixture," in the Physics of Fluids, Vol. 9, No. 6, June 1966.

Further work on baro-diffusion effect on time-dependent problem of binary mixtures of two perfect gases is in progress.

Nomenclature

ρ = density of the mixture

$\vec{u}$ = momentum per unit mass of the mixture

c = mass concentration of the heavier species

p = thermodynamic pressure of the mixture

m_1 = molecular "weight" of heavier species

m_2 = " " lighter "

Ω = angular velocity of swirling motion

μ = coefficient of dynamic viscosity

D = coefficient of diffusion

k_p = baro-diffusion ratio

R = universal gas constant

T = absolute temperature

∇ = del operator

$\vec{F}$ = $+\rho\vec{g}$ = body force

2. <u>Radiative Transfer for Parallel Streams of Radiating Gases</u> (Y.C. Whang, to appear in the September issue of the AIAA Journal). The radiative and convective heat transfer between two parallel streams of radiating gases is studied. The Rosseland diffusion approximation and the radiation slip boundary condition are used to describe the problem. The solution in closed form is obtained. This solution shows the transition between the black body formulation for the optically thin regime and the Rosseland diffusion formulation for the optically thick regime. The thickness of radiation layers is also calculated.

3. On Mass Transfer Between Two Parallel Streams (Y. C. Whang, Report No. 66-007, June 1966, submitted for publication). The convective and diffusive mass transfer between two parallel streams of gases is studied in this paper. When the two gases in the freestreams are of different densities, the flow field is disturbed due to mass diffusion. Solutions for mass concentration, flow velocity, and density are obtained in closed forms. Mass transfer between two parallel streams in transition regime is also studied, slip boundary condition is used, its solution shows a smooth transition between the free-molecule solution and the continuum solution.

(D) Stability of Helmholtz Flow (T. Eisler)

The stability of the Helmholtz profile in a stratified flow with an unstable density gradient has been studied. It is found that the convective and shear instabilities are essentially separate. It is noted that the shear gives rise to an amplified mode at right angles to the direction of the mean flow.

(E) Publications

The reports are shown in the following list:

Tech. Rept. No. (SSAP)	Author	Title	Date Submitted	Published
65-001	T. Kao	Stability of Two-Layer Viscous Stratified Flow Down an Inclined Plane	2/4/65	Physics of Fluids, 8, 5 May 1965
65-002	H. Pao & C.C. Chang	Magnetohydrodynamic Boundary Layer Between Parallel Streams of Different Magnetic Fields and Temperatures	2/4/65	AIAA Journal 4, 8, Aug. 1966
65-003	T. Eisler	Stability of a Shear Flow in an Unstable Layer	2/4/65	Physics of Fluids, 8, 9, Sept. 1965

Publications (cont'd)

65-005(a)	T. Kao	On the Establishment of Density Profile for the Flow of a Two-Fluid Single Phase Gas Mixture	4/9/65	NASA CR-330
65-005(b)	T. Kao	Establishment of Concentration Profiles for a Binary Fluid for Duct and Swirl Flow	6/18/65	Physics of Fluids 9, 6, June 1966
65-006	H. Pao	The Stability of Swirling Flow of a Viscous Conducting Fluid in the Presence of a Circular Magnetic Field	6/18/65	Physics of Fluids 9, 6, June 1966
66-001	Y.C. Whang	Radiative Transfer for Parallel Streams of Radiating Gases	2/1/66	To appear in AIA Journal, Sept. 1966
66-002	T. Eisler	Stability of a Jet in a Stratified Gas ~~G~~low F	2/1/66	Submitted for publication
66-007	Y.C. Whang	On Mass Transfer Between Two Parallel Streams	7/1/66	Submitted for publication
66-011	T. Eisler	Stability of Helmholtz Flow in an Unstable Atmosphere	7/15/66	Submitted for publication

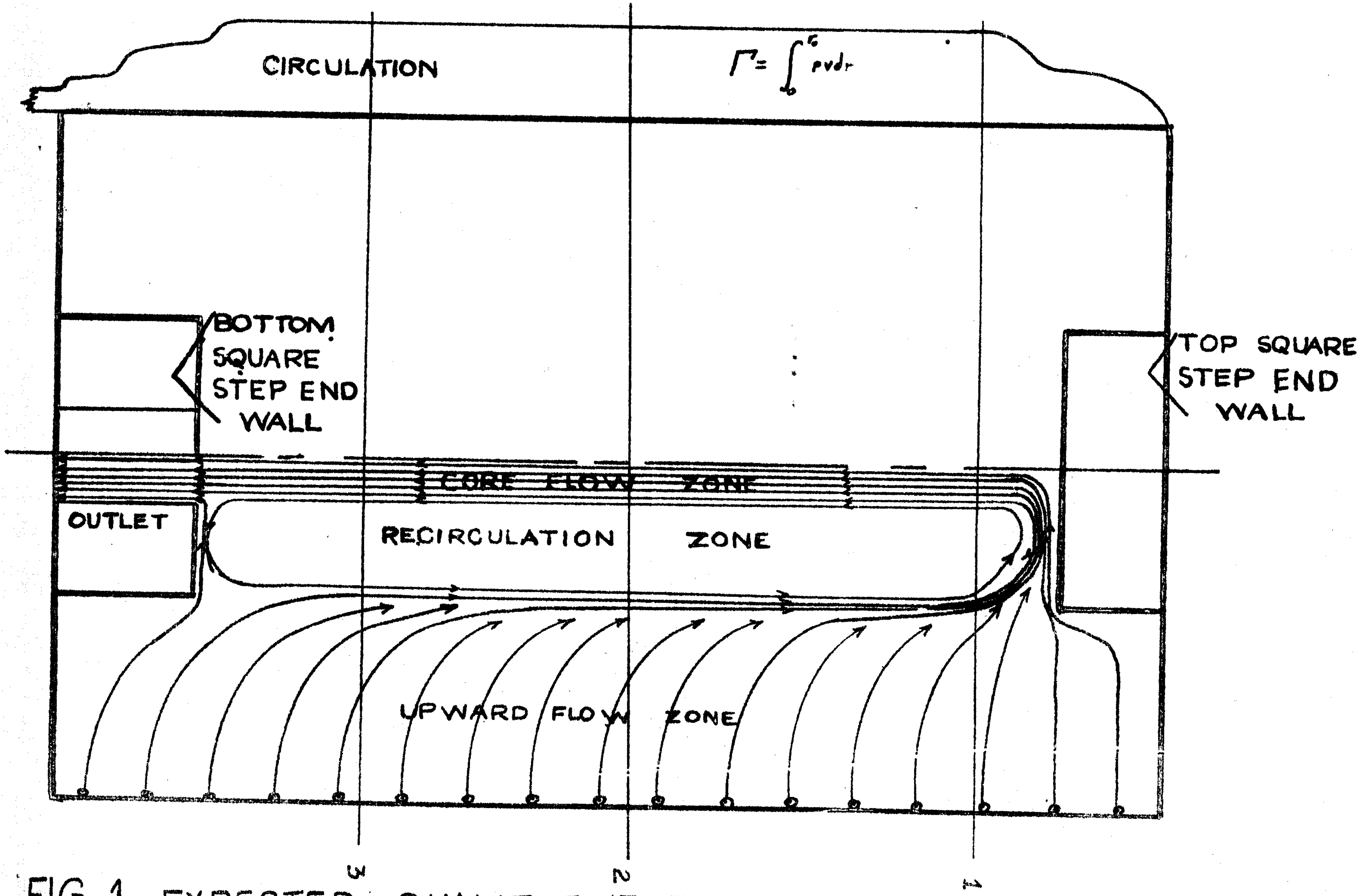

FIG 1 EXPECTED QUALITATIVE FLOW PATTERN OF CYLINDRICAL CAVITY REACTOR MODEL WITH SQUARE STEP END WALLS (TENATIVE)

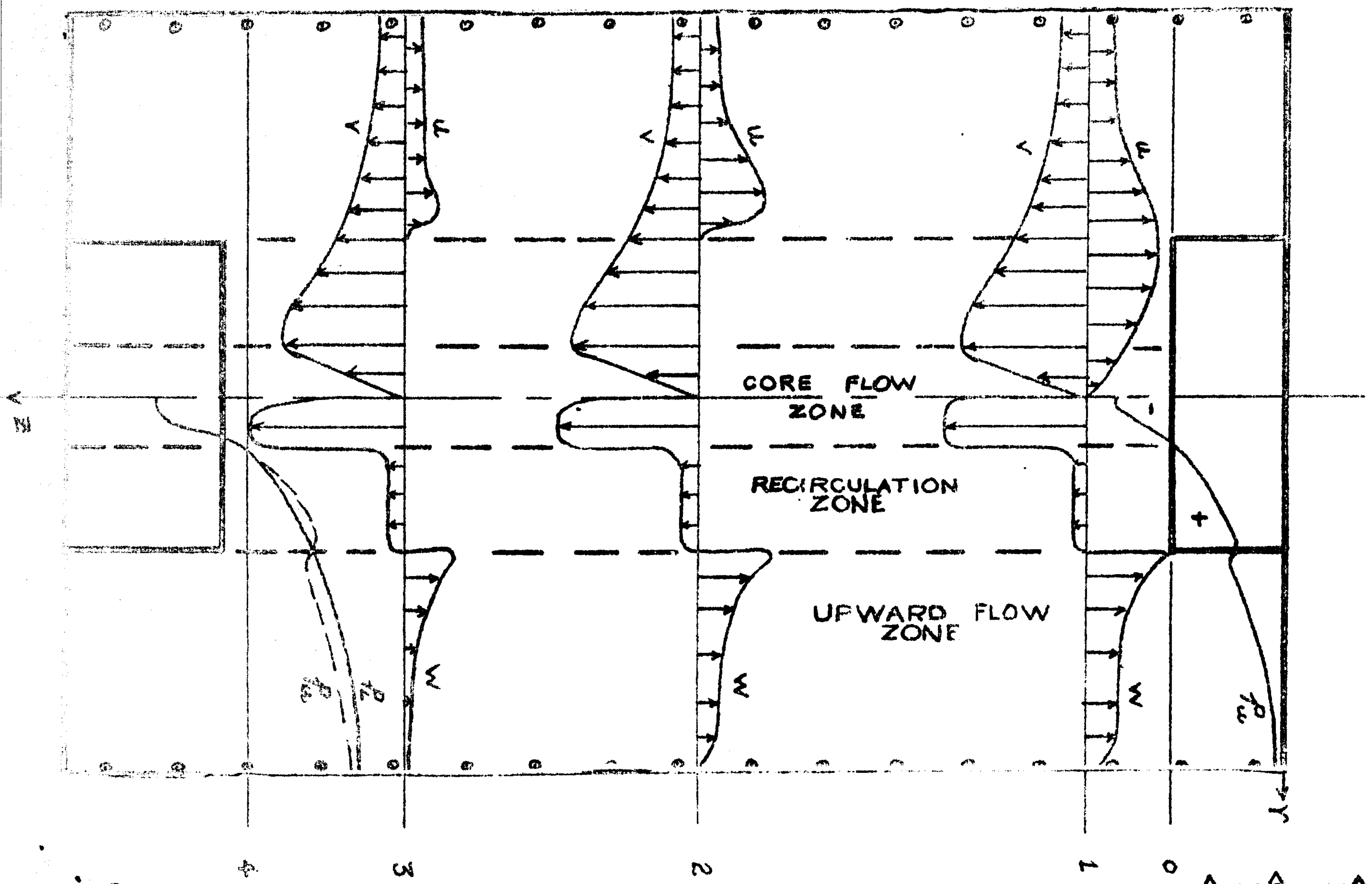

FIG 2 EXPECTED QUALITATIVE VELOCITY COMPONENTS $u\hat{r}, v\hat{\theta}, w\hat{z}$ AT STATIONS 1, 2, 3 AND STATIC PRESSURES AT STATIONS 0 AND 4 (TENTATIVE)