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Report No. 113-30
Part I

TWO PHASE FLOW AND HEAT TRANSFER
IN POROUS BEDS UNDER VARIABLE
BODY FORCES

Final Report
Part I

By Julian O. Doughty and Harold R. Henry

Project Director:

Harold R. Henry, Ph.D.
Professor of Engineering Mechanics
University of Alabama

Submitted to

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

Contract No. NAS8-21143
University of Alabama No. 22-6560

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PREFACE

This is Part I of a seven part Final Report on work under Contract No. NAS8-21143 between the George C. Marshall Space Flight Center and the University of Alabama. The purpose of this entire project has been to perform analytical studies and laboratory tests related to designing an orbital experiment, i.e., perform theoretical studies, develop experimental hardware and conduct experiments for the purpose of establishing the feasibility of investigating two-phase fluid flow and thermal transfer in porous beds in a reduced gravity environment. This purpose has been accomplished and the results of the study are contained in the seven parts as indicated below:

Part I explains the motivation for the project with reference to expected fundamental scientific achievements and a description of applications related to space-flight and ground-based devices.

Part II is primarily an experimental study of the factors influencing two-phase flow. Analytical work and dimensional analysis are used to provide a framework for the presentation of the experimental data. The results are such that they allow extrapolation to reduced gravity situations.

Part III is an analytical and computer-based study conducted on an idealized model of two-phase flow in a porous material. It clarifies the relations among pressure gradient, surface tension, inertia and

gravity forces.

Part IV is a systems analysis of the transients occurring in an assumed model of the proposed flight experiment for boiling and vapor bubble studies. The technique of digital simulation was employed in the analysis.

Part V is an account of the development of a two-phase mass flow meter utilizing porous cartridges as the primary elements. After calibration, the only measurements which are required to determine the flow are the pressure drop across each cartridge and the temperature between cartridges.

Part VI describes the development of the bread board package including test models of two experimental flow channels with pumps, motors, instrumentation and peripheral equipment for power and data recording. Also included are an account of basic experiments on the vapor-bubble breadboard channel.

Part VII is an Experiment Implementation Plan. It details the selection of porous materials, liquids and gases. It also includes the parameters necessary for the design and development of a flight experimental system. It also identifies, defines and establishes the general specifications for system elements requiring further development.

1. OBJECTIVES

The overall objective of this experiment is to determine the behavior of two phase vapor-liquid and/or gas-liquid flow through porous beds, screens and membranes in low gravity environments. This embraces the more detailed objectives listed below:

1. An important part of the experiment will be to obtain data useful in developing fundamental relations among capillary forces, viscous forces, pressure gradient forces, inertia forces, gravity forces, and heat transfer considerations. Varying the body force is necessary to obtain data for the complete range of parameters involved.

2. Since there are practical applications in space travel which concern two-phase phenomena in porous media, a major objective of this experiment is to accumulate data which will be useful in solving the related practical problems encountered in space travel.

3. Much of the information obtained in this experiment will be useful in non-space related applications. Examples are water purification schemes using porous beds, oil and natural gas production from porous geological formations, disposal of contaminants in ground water formations, and flow through packed beds in chemical engineering processes. One objective of this experiment is to provide data that will be useful in these and other non-space applications.

2. SIGNIFICANCE

When one considers ratios among the principal forces involved, namely capillary forces, viscous forces, pressure gradient forces,

gravity forces and buoyancy forces due to thermal expansion, the following dimensionless parameters may be formed:

$$\frac{\text{Inertial Forces}}{\text{Viscous Forces}} = \text{Reynolds number}$$

$$\frac{\text{Gravity Forces}}{\text{Capillary Forces}} = \text{Bond number}$$

$$\frac{\text{Pressure Gradient Forces}}{\text{Viscous Forces}} = \text{Pressure coefficient}$$

$$\frac{\text{Inertia Forces}}{\text{Capillary Forces}} = \text{Weber number}$$

$$\frac{\text{Thermal Buoyancy Forces}}{\text{Viscous Forces}} = \text{Grashof number}$$

Ground-based tests can be run in which each force except gravity can be varied from a very small value to a very large value by changing properties of the fluid or the porous medium or by changing the flow characteristics.

The fundamental significance of the flight experiment lies in the fact that there are certain combinations of parameter sizes which are virtually impossible to obtain on the ground.

Small Bond number, large Reynolds number, and small Pressure coefficient are impossible to obtain without reducing gravity. This is because in the normal gravity field, a small Bond number requires extremely small pores to give a high capillary force; these small pores also cause the viscous force to be large and thus Reynolds number is small unless the velocities are high; the pressure coefficient cannot be low unless the velocity and Reynolds number are low; thus this combination cannot be achieved on the ground.

Also low Bond numbers with the necessary small pores in ground-based experiments result in low Weber numbers. The combination of large Weber numbers and small Bond numbers can be obtained only by decreasing gravity.

Thus experiments performed in a reduced gravity environment will allow study of the important ranges of parameters which cannot be investigated on the ground.

A very practical significance of this experiment lies in the applications to space travel. Some of these are discussed below.

Phase Separation

When a porous material is submerged in a wetting fluid which contains bubbles of a non-wetting fluid, the pores will be occupied by the wetting fluid and no non-wetting fluid will move into the material unless the driving pressure differential is greater than the capillary pressure difference. If the material is previously saturated with the non-wetting fluid before being submerged, all the non-wetting fluid will be driven out as the wetting fluid fills the voids.

When a mixture consisting of liquid and gaseous phases is passed over a screen or thin porous board, the wetting fluid will tend to move through the board and the non-wetting fluid will not.

These capillary phenomena provide a possible means of phase separation of liquid and gas/vapor in low gravity environments.

Mass Metering

Because of the difficulty in separating gases and liquids in the absence of gravity, the metering of two phase flow is a problem associated with reduced gravity environments. A porous material will exhibit a selective relative permeability to each of two fluid phases simultaneously flowing through it. This fact raises the possibility of using porous cartridges in a pipe as the principal elements in a device to meter the mass flow of two phases. This concept will be tested as part of the proposed project.

Vortexing and Turbulence Reducers

Fine mesh screens or thin porous blankets have been found effective in reducing vortexing tendencies and turbulence in the entrance to feed lines from propellant tanks. If there is boiling or vaporization, as will be the case with cryogenic liquids, the vapor will tend to collect at the screen and, because of capillary forces, will act as an obstruction to the movement of liquid through the screen. Some studies have sought to predict analytically the effect of absence of gravity or zero Bond number for static conditions with extremely simple capillary geometry. However, these results cannot be extrapolated to the complex capillary geometry of porous flow straighteners or screens under dynamic conditions in a low gravity environment.

Water Purification Schemes in Space Flight

Almost every scheme recommended for the reclamation of waste water in the closed environment of space travel involves flow through membranes and porous beds such as activated charcoal for the removal of impurities. In the case of an electrodialysis system, porous material consisting of thin membrane-like layers with some serving as anion permeable membranes and others serving as cation permeable membranes are recommended. In the vacuum pyrolysis system it is generally recommended that the liquid flow through porous catalyst beds. Often, regardless of the principal method of removing wastes, a final filter is recommended.

In some cases it is difficult to maintain flow in the system without the ingesting of some gas into the liquid flow scheme. However, even if there is none of the gaseous phase present in the entrance to the treatment apparatus, the pressure drop required for flow through the porous beds may cause considerable dissolved gas to come out of solution. In

some cases the permeability of the porous bed may be decreased by as much as 30% by the presence of as little as 10% gas by volume. Moreover, the purifying or exchange function of the porous bed is efficient only when there is a maximum liquid-solid area of contact. This is obviously reduced when vapor or gas bubbles are present.

The fundamental results of this study will be applicable in many non-space related areas. Tests run with reduced gravity will allow combinations of dimensionless parameters which are impossible to obtain under normal gravity and which will lead to a much better general understanding of capillary phenomena in two phase flow. Some of the non-space applications are discussed below:

Water Purification Schemes in Ground-Based Plants

Where porous or permeable beds are utilized in non-space water purification schemes, fundamental information on the effect of air bubbles within the porous material will be helpful. Therefore the information obtained in these proposed studies will be useful in non-space related water purification.

Oil and Natural Gas Production

Oil and natural gas are found in porous geological formations usually with brine in close conjunction. The relative positions of the three fluids are determined by the relative gravitational forces. Hence, the gas will be at the highest elevation, oil next and brine at the lowest elevation. The sinking and pumping of oil wells will disturb the natural equilibrium of the configuration and two (or three) phase flow always results. Also in oil production, water is often pumped into neighboring wells to force oil from a particular well.

These examples of two phase flow occur with the relative gravitational (or buoyancy) effect between phases varying quite widely. When oil and gas or brine and gas are the two phases, the weight (or gravitational force) of the gas is almost negligible. However, when brine and oil are the two phases, the relative effect of gravity is more nearly equal in the two phases. This is a case of reduced relative gravitational effect.

The results of this proposed study will be directly applicable to oil and natural gas production.

Disposal of Contaminants in Ground Water Formations

As industrialization increases, the waste disposal problem increases. Some dilute wastes or contamination inevitably find their way into the ground thus contaminating the underground water. In some areas when water users do little more than raise the temperature (as for instance, water used in air conditioning cooling towers), local ordinances provide for the water to be pumped back into the geological formation from which it was obtained.

In these cases there is a density or temperature difference or both between the contaminant and the native water. Sometimes there are also oils or gases in the contaminant so that capillary forces are present. The fundamental studies and testing proposed herein will be helpful in evaluating the movement of these contaminants.

Chemical Engineering Processes

Two phase flow through packed porous beds are part of many processes in chemical engineering applications. In some cases it has been shown that the presence of a gas in catalyst beds greatly increases the thermal conductivity over that for single phase liquid flow. In other

cases gas bubbles move upward through porous beds fluidized by liquid flow. The movement of the gas bubbles and the fluidization are both phenomena which depend upon gravity. Fundamental studies showing the effect of varying gravity should lead to a better understanding of these processes.

3. DISCIPLINARY RELATIONSHIP

(a) Brief History of Related Work

Much of the fundamental work in the field of flow in porous media has been done by chemical engineers, geophysicists and petroleum engineers. A large body of literature containing fundamental studies of mass dispersion, including the effect of density gradients and two phase flow in porous media has been directed toward applications to flow in water bearing aquifers (i.e., porous geological formations), to flow in oil bearing and gas bearing sands, and to flow through catalyst beds.

The principal investigator has provided direction for several theses which have been written in this and related areas (Adams, 1965; Lin, 1964; Miller, 1966; Toth, 1966; French, 1967). He has recently completed a research project consisting of an analytical and laboratory study of the effects of thermal and density gradients in saturated porous media (Henry, 1967).

One of the most significant results of this recently completed study is that the effective thermal diffusion coefficient in flow through porous media is shown to be an order of magnitude larger than the usual molecular diffusion coefficient. This is similar to results obtained by the principal investigator and others concerning mass diffusion in porous media. This large heat diffusion coefficient is of utmost importance in obtaining internal energy balances for the determination of whether or not the liquid will vaporize locally.

Because of its importance in many fields of engineering and especially in ground water technology, chemical engineering, and petroleum reservoir technology, the phenomenon of dispersion accompanying miscible

displacement in saturated porous material has received much attention in recent years. As a natural consequence of the complexity of the subject, most investigations have been concerned with the case where the two fluids have similar mechanical and thermal properties. Such studies are exemplified by the following recent papers (Adams, 1965; Banks and Ali, 1964; Bear, 1961; Gottschlich, 1963; Harleman and Rumer, 1963; Ogata, 1964; Poroh, 1965; Schiedegger, 1958).

Recent studies have also been made on flow with density, gradients, i.e., the mixing of two miscible fluids of different density. They fall into two categories; namely, those that assume a step change in density at a sharp interface and those that consider a zone of dispersion where the dispersion equation and the equation of motion are coupled because of the buoyancy change associated with the change in concentration of the solute. Representative recent papers which fall in the first category are: (De Josselin de Jong, 1960; DeWiest, 1961; Henry, 1959, 1962, 1964b; Lin, 1964). Some recent papers which treat the region of dispersion wherein there is a density gradient and associated buoyancy forces are: (Henry, 1961, 1964a).

These studies on single phase flow or flow of miscible fluids of course do not yield information on two phase flow but do provide necessary relations for the evaluation of parameters within one of the phases.

Much of the investigational work on two phase flow (or flow of immiscible fluids) in porous media may be divided into the following three categories. The first category treats a "mixture" of the two fluids in which small bubbles of one phase exist uniformly embedded in the second phase and flow of both occurs simultaneously. In this case

the concept of relative permeability becomes important (Collins, 1961). It has been shown experimentally that as the saturation of the porous material by the second phase increases from zero, the permeability of the material to the first fluid decreases sharply. This is shown qualitatively in Figure 3.1. This phenomenon would be important in water purification schemes if the pressure drop through porous beds were to allow air or other gases to come out of solution in small bubbles throughout the porous mass. There have been many studies which describe some aspect of this type of flow as it applies to flow through catalyst beds. An example is the work by Weekman and Myer (1965) in which they observed that the presence of a gas phase greatly increases the effective thermal conductivity over that for single phase liquid flow.

The second category is the displacement of one phase by a second phase. Collins (1961) discusses this type of flow and points out that

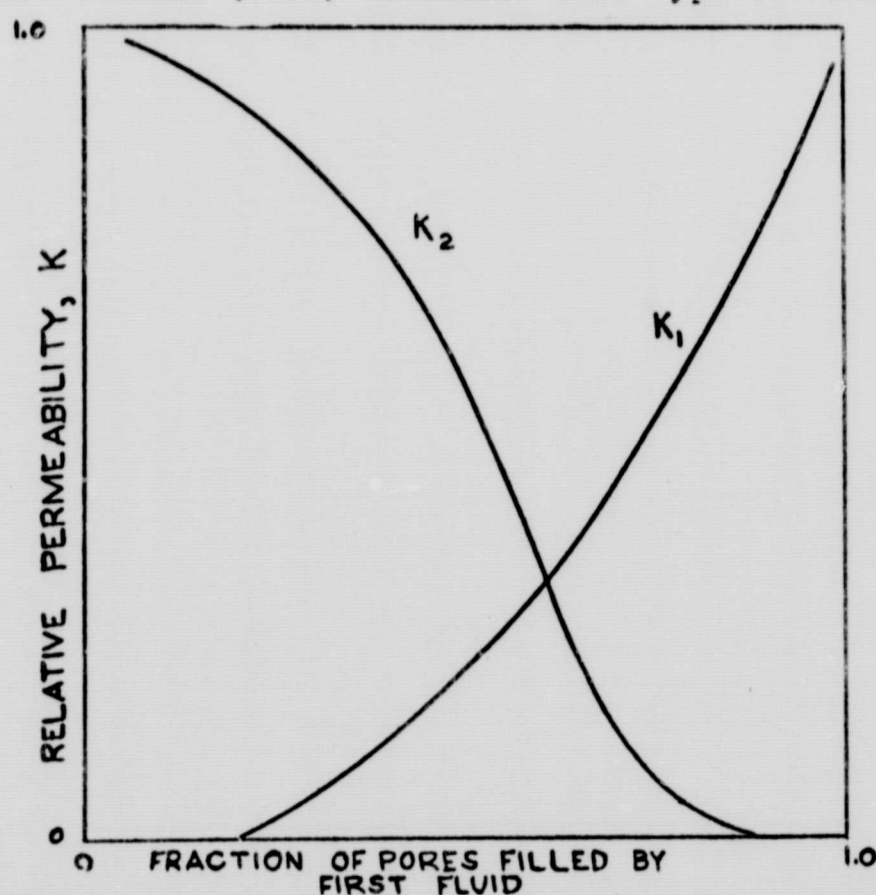


Figure 3.1. Relative Permeability Curves (After Collins, 1961)

there is a critical velocity below which the line between the advancing fluid and receding fluid is very uniform. For velocities greater than the critical value, extreme viscous fingering may occur. This is illustrated in Figure 3.2.



Figure 3.2. Formation of Viscous Fingers. (After Blackwell, 1959)

The third category treats the movement of large individual bubble formations through the porous materials. Østergaard (1961) studied experimentally the dynamics of a gas bubble as it moved upward through a porous bed fluidized by a liquid. Goring and Katz (1962) studied bubble rise in a packed bed saturated with liquids for the primary purpose of determining drag coefficients for the bubbles.

(b) State of Present Development in Field

It appears that there has been no previous work on two phase flow in porous media under reduced gravity conditions. This conclusion is based upon a general familiarity of the field by the principal investigator and by the following searches.

(1) A library search of all publications reviewed in Engineering Index and Applied Science and Technology Index for the past 10 years.

(2) A communication from Professor D. L. Katz at the University of Michigan who reported that he knows of no low gravity studies in porous media flow. (Professor Katz has done work on two phase flow in porous media and Professor Clark at the University of Michigan is doing work on two phase phenomena in clear liquids under low g).

(3) A communication from Mr. R. Siegel at the Lewis Research Center in Cleveland, Ohio, who has studied the effects of reduced gravity on nucleate boiling bubble dynamics and who indicated that he knew of no studies of two phase porous media flow under reduced gravity conditions.

(4) A communication from Professor B. T. Chao at the University of Illinois who has performed drop tower experiments in fluid mechanics and who revealed knowledge of no further information in this area.

(5) A request to the Science Information Exchange in Washington D.C. for information on current research projects on two phase flow in porous media under reduced gravity resulted in a search of S.I.E. files which indicated that there is no other current research being performed in this area.

4. Space Flight Applications

The occurrence of mixed two-phase flow is more natural in a very low or zero gravity environment than in the normal Earth-surface gravity environment. The validity of this can be intuitively supported by considering the action of mixed phases in a closed vessel. In the presence of gravity, unequal body forces are generated on the different fluid components resulting in a natural separation of the phases with the more dense liquid seeking equilibrium in the bottom of the vessel. However, this natural separation is lost in zero gravity and the phases mix randomly unless other separation inducing forces are present.

The tendency for fluid phases to mix in space is the source of many problems having to do with the management, processing, and storage of fluids. The problems range in complexity from that of providing air-free liquid nourishment to the astronauts to that of providing vapor free liquid to the engine system. It is evident that a thorough understanding of two-phase flow in low gravity environments is essential for recognition and solution of associated problems.

One of the promising geometries for management and processing of two-phase flows in space is offered by porous media, because this geometry allows control of capillary forces which are independent of gravity. An attempt is made here to identify a few of the situations related to space flight where basic knowledge of the mechanics of two-phase flow, especially two-phase flow in porous media, will be required for design information.

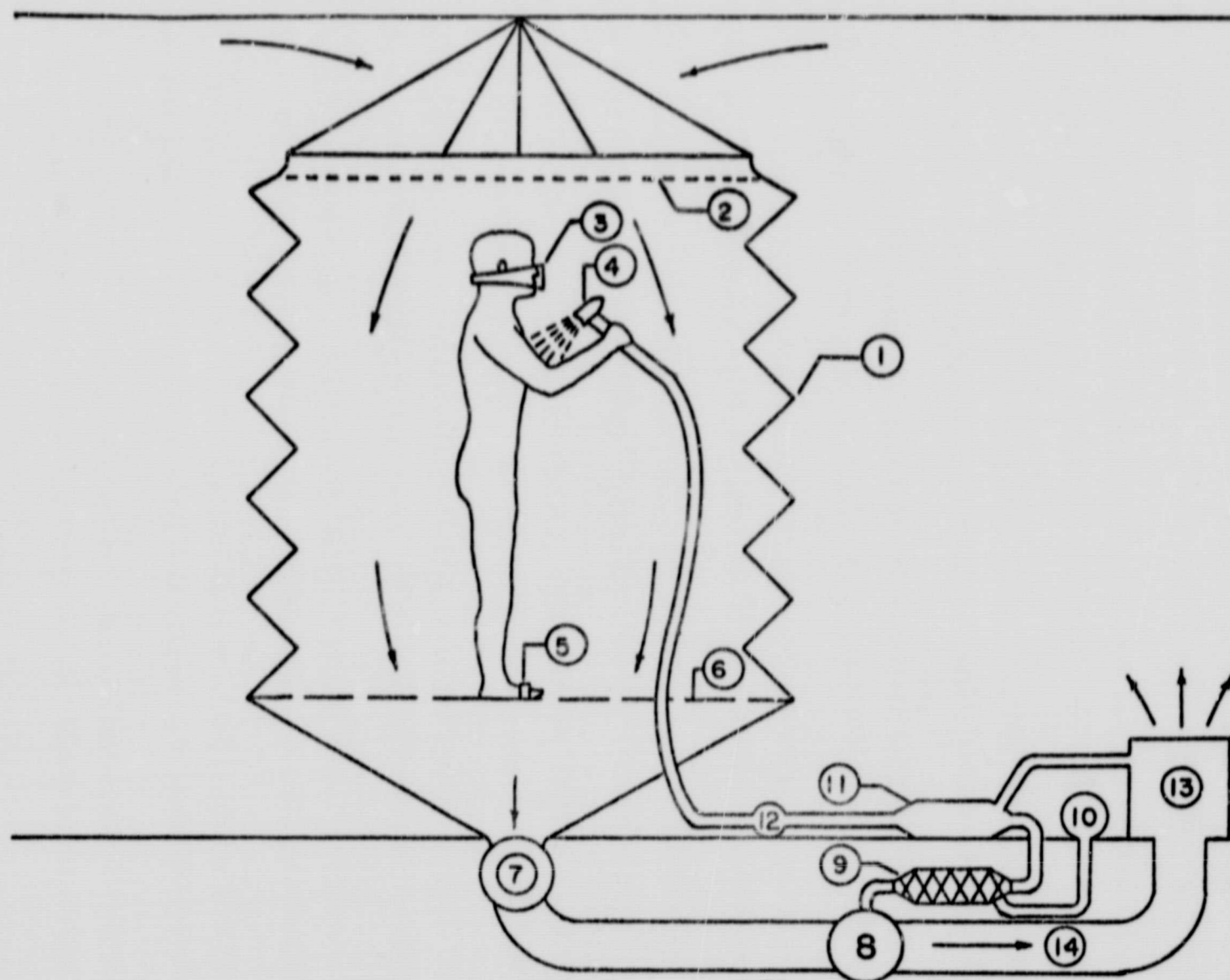
4.1 Collapsible Shower

On long duration flights, it is planned for the astronauts to shower every fifth day in a closed shower. A possible arrangement of such a system, where water is removed from the shower by a forced draft of air, is illustrated in Figure 4.1.

The basic shower housing (1)* will probably be constructed from a hydrophobic polymer material. The hydrophobic nature will help prevent accumulation of water on the shower wall in regions of low draft velocity. A screen which will pass air and reject water (2) will be needed at the mouth of the shower to prevent water from splashing out into the cabin. A coarse meshed screen (6) with a foot holder (5) will anchor the astronaut; otherwise, the momentum flux from the shower nozzle (4) and drag created by the air draft would create positioning difficulties for him. A pump (7) capable of passing mixed phase flow will provide the air draft for water elimination inside the shower and also a pressure head for the shower water treatment system.

The first process in the water treatment will be initial separation of the shower water and draft air, accomplished by a centrifugal separator (8). From this, the separated air will be directed through a de-humidifier and returned to the space craft cabin. Moisture collected by the de-humidifier will be returned to water storage (11), and water separated from the shower discharge will be routed through a porous bed purifier (9) for removal of contaminants and subsequently returned to storage (11).

*Numbers in parenthesis refer to identification numbers on the appropriate illustration.



① COLLAPSABLE CONTAINER

⑧ CENTRIFUGAL SEPARATOR

② HYDROPHOBIC SCREEN

⑨ POROUS BED WATER PURIFIER

③ HYDROPHOBIC SCREEN

⑩ WASTE STORAGE

④ SPRAY NOZZLE

⑪ WATER STORAGE

⑤ FOOT HOLDERS

⑫ PUMP

⑥ LARGE-MESH SCREEN

⑬ DE-HUMIDIFIER AND AIR RETURN

⑦ PUMP

⑭ AIR DUCT

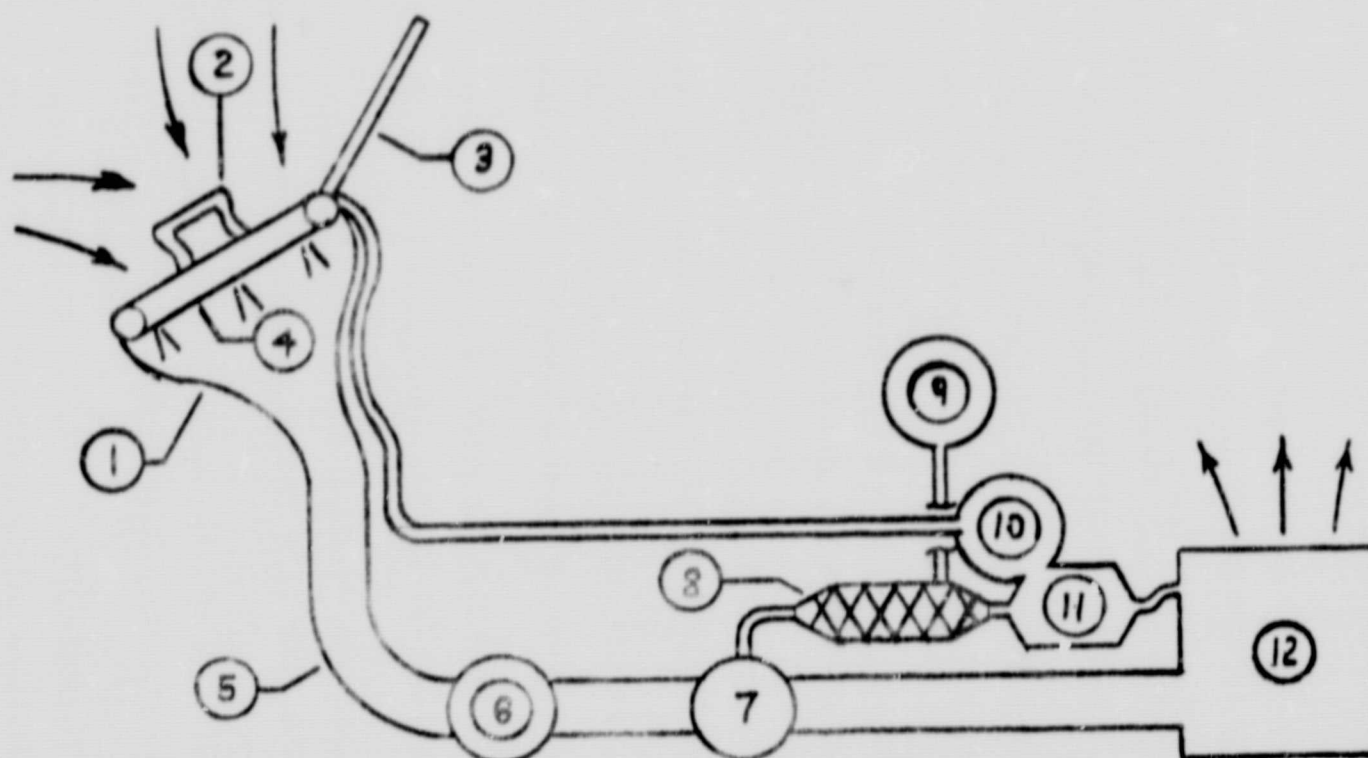
FIG. 4.1 SCHEMATIC DIAGRAM
OF ZERO GRAVITY SHOWER

The astronaut will be provided with a mask (3) to prevent nasal ingestion of water. The essential feature of the mask will be a hydrophobic screen. Such a mask will provide much more freedom of movement than the alternative, a snorkle arrangement.

In the shower system envisioned, two phase flow through porous media occurs in several places and in very different conditions and geometries. Phase separation involving mixtures that are predominantly gaseous by volume is required by the face mask, the screen at the mouth of the shower, and the centrifugal separator. The porous bed water purifier will operate with a mixture that is predominantly liquid, receiving only traces of air not removed by the phase separator; none-the-less, its operation would be adversely affected by air accumulation, so a knowledge of the mechanics of two-phase flow is essential for proper design of this bed. Also, the filter system in the de-humidifier will undoubtedly involve two phase flow. Thus, the overall system illustrates the need for a basic understanding of two phase flow over a wide range of controlling parameters.

4.2 Urinal System (Figure 4.2)

Many of the problems and techniques involved in the shower system are also present in the urinal system. The system envisioned has a urine bowl connected to the processing system by flexible connections (5) to facilitate storage when not in use. When in use, the bowl (1) will be held in place by hand and the urine will be directed into the bowl exhaust by a forced draft of air and a water film from the spray ring (4). Mechanically, the processing system for the water-urine solution will be very similar to that of the shower system, and the same general comments apply.



- | | |
|----------------------|------------------------------------|
| (1) Urinal | (7) Centrifugal Separator |
| (2) Handle | (8) Porous Bed Purifier |
| (3) Cover | (9) Waste Storage |
| (4) Water Spray Ring | (10) Pump |
| (5) Flexible Hose | (11) Water Storage |
| (6) Pump | (12) De-Humidifier and Air Cleaner |

Fig. 4.2 Schematic Diagram
of Urinal System

4.3 The Packed Bed Nuclear Reactor

The packed bed is of considerable interest as a nuclear reactor configuration (see Figure 4.3). Nuclear fuel pellets are immersed in a flowing liquid which serves to transfer the heat generated to some heat sink for use, and to simultaneously cool the bed to acceptable operating temperatures. The flow mechanics of the bed are therefore intimately coupled with the operation of the reactor.

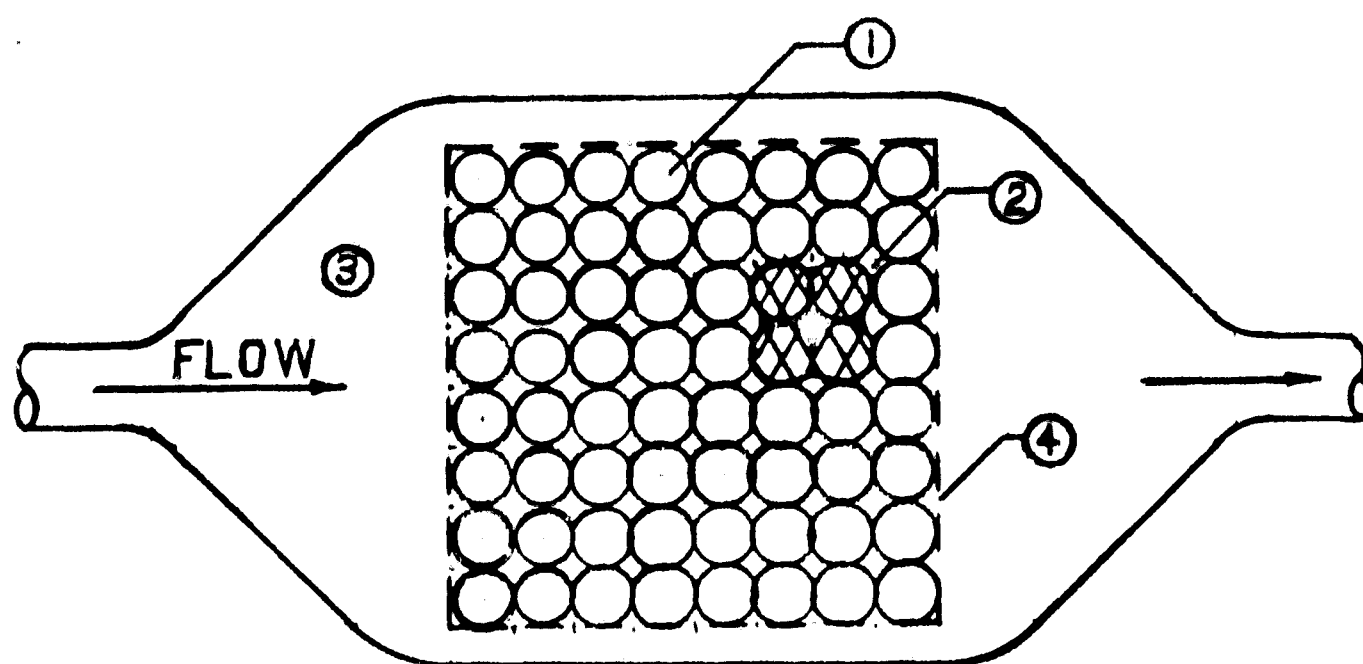
Studies reported in Part II of this Final Report show that Darcy's equation is incapable of predicting clear liquid flow losses in a packed bed at moderate Reynolds numbers (i.e., where inertial and viscous effects are comparable); however, it has been shown that such losses can be correlated with the form:

$$\frac{\partial}{\partial x} (P + \Omega) \frac{d^2}{\mu_L V_L} = \alpha_1 + \beta_1 R_{e_L}$$

where

- P = pressure
- Ω = gravity potential
- d = sphere diameter
- μ_L = liquid viscosity
- V_L = bulk liquid velocity
- α_1 = experimental constant
- β_1 = experimental constant
- R_{e_L} = Reynolds number

In this form, α_1 is related to the viscous effects and β_1 to the inertia effects.



- (1) Spherical Fuel Pellets
- (2) Vapor Accumilation
- (3) Liquid Heat Transfer Agent
- (4) Fuel Pellet Container

Fig. 4.3 Packed Bed
Nuclear Reactor

The simplest operation of the reactor would be in a regime such that the liquid temperature remained everywhere below local vaporization temperature; however, for space applications considerable weight reduction in liquid required for a given heat transfer rate could be accomplished by allowing local boiling inside the reactor, thus using the heat of vaporization much as a heat pipe does. To design for this type of operation it is absolutely essential to completely understand the flow mechanics of vapor-liquid flow in packed beds. Any stagnant vapor pocket in the bed would severely reduce the local heat transfer rate and be disastrous: probably resulting in melting of fuel pellets.

Investigation of vapor-liquid flow in packed beds is reported in Parts IV and VI of this Final Report together with a description of the bread-board models in Part VI. The study reported in Part II results in a form to correlate mixed phase flow pressure drops for moderate Reynolds numbers:

$$\frac{\partial}{\partial x} (P + \Omega) \frac{d^2}{\mu_L V_L} + \frac{V_g - V_L}{V_L} \left(\frac{3}{4} \Phi Sg (\alpha_2 + \beta_2 R_{e_r}) + \frac{3}{4} (1 - \Phi) (\alpha_1 + \beta_1 R_{e_1}) \right) = 0$$

where the symbols are identical to those in the clear liquid equation with the addition:

V_g = bulk gas velocity

Φ = porosity

Sg = quality (based on volume ratios)

$$R_{er} = \frac{(V_g - V_L) \rho_L d}{\mu_L}$$

α_g = experimental constant

β_g = experimental constant

Although much of the phenomena can be investigated in an Earth gravity environment, a complete investigation requires tests conducted in very low and zero gravity environments. A study of the vapor entrainment phenomena is of particular significance in the low gravity environment because the condition is associated with a low Bond number.

4.4 The Heat Pipe

The heat pipe is a simple, inexpensive device that can transfer as much as 500 times as much heat per unit weight as a solid thermal conductor, and it also offers great flexibility in design geometry. These characteristics make it an extremely attractive device for transferring and dissipating heat in spacecraft applications. Doubtlessly, the heat pipe will be used with increasing frequency in space vehicle designs.

The simplest geometry for a heat pipe is a straight, sealed tube containing a porous wick material which extends the length of the tube and is saturated with suitable liquid (see Figure 4.4). In operation the liquid is evaporated at the heat addition end and condensed at the heat sink end. Thus, the heat transfer rate is given by:

$$Q = \dot{m} h_{fg}$$

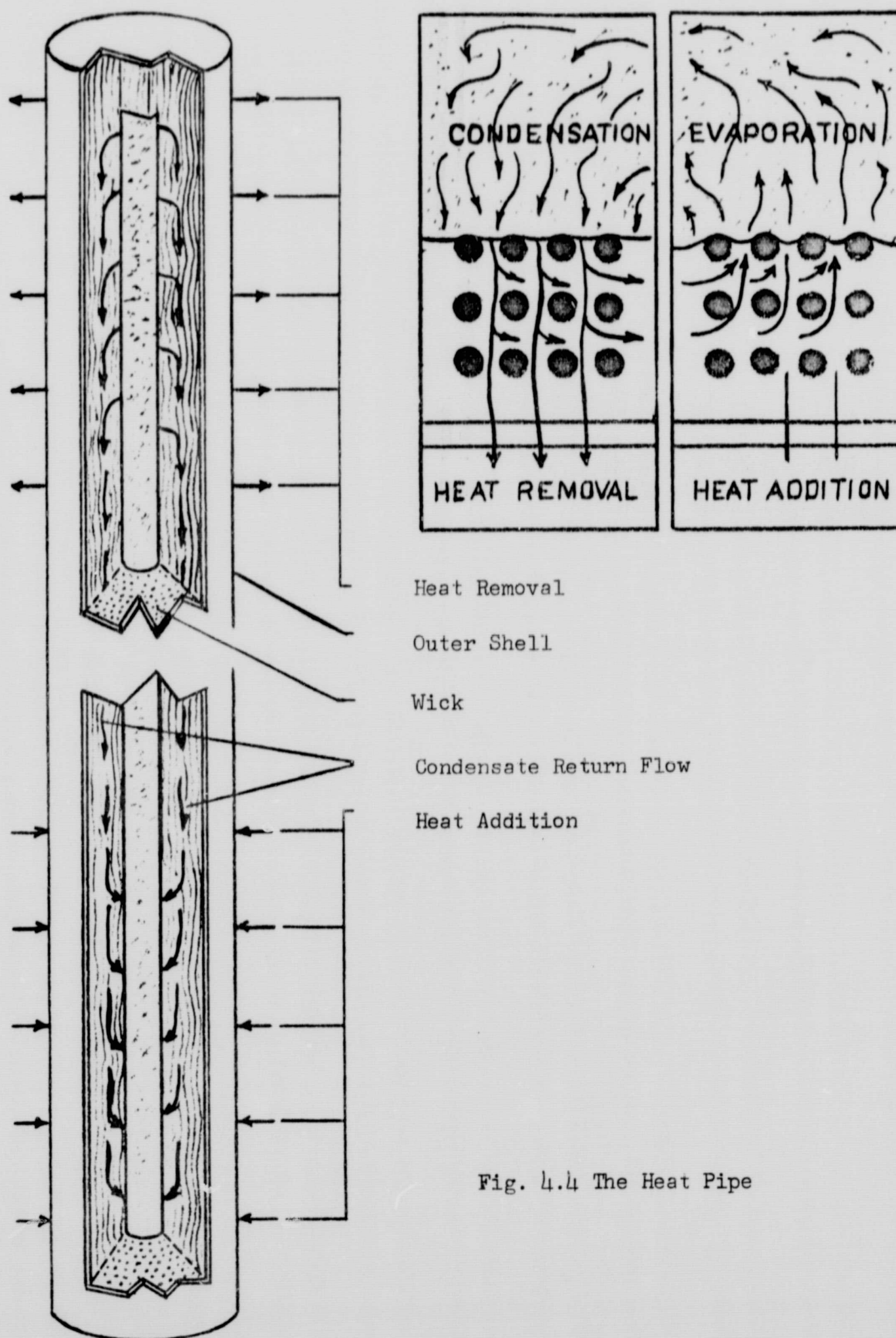


Fig. 4.4 The Heat Pipe

where

Q = heat transfer rate

$\dot{m}$ = evaporation rate

h_{fg} = heat of vaporization

The heat transfer rate is thus limited by the rate at which liquid can be supplied to the heat addition area by the porous wick, and in the absence of gravity, the sole driving force is supplied by surface tension. The pressure drop generated is expressed by:

$$P_b - P_c = 2\sigma \left(\frac{\cos \gamma}{r_b} - \frac{\cos \delta}{r_c} \right)$$

where

$P_b - P_c$ = pressure difference between boiler and condenser

σ = surface tension

r = meniscus radius (b and c refer to boiler and condenser)

γ = wetting angle in the boiler

δ = wetting angle in the condenser

and the maximum heat transfer rate can be expressed in terms of design geometry and fluid properties as:

$$Q = \frac{\sigma A D h_{fg}}{b V L}$$

where

A = wick flow area

D = hydraulic diameter of an individual capillary

b = capillary geometry constant

V = kinematic viscosity of the liquid

L = capillary length

The last equation shows that the maximum heat transfer rate is directly proportional to the wick flow area and would, therefore, be impaired by vapor entrainment in the wick. In operation vapor bubbles will form at the pipe wall in the heat addition area and must be subjected to a large enough pressure gradient to sweep them through the wick into the vapor return channel. The mixed phase investigation reported in Part VI yields information pertinent to this problem.

4.5 Volumetric Measurement of Two-Phase Components

The need for simple, reliable measuring techniques for two-phase flow is evident. The study reported in Part V of this Final Report has demonstrated the feasibility of measuring the flow rate of both flow components with two simple porous cartridges. (See Figure 4.5). The heart of the system consists of two porous beds of dissimilar configuration in series in the flow. To accomplish flow component measurement it is necessary to measure only the pressure drop across each porous cartridge and the mixture temperature. With dissimilar flow through the cartridges, the pressure gradients across each are independent functions of the flow rates of each phase. Therefore, a cartridge system can be calibrated for these functions. A typical calibration is illustrated in Figure 4.6, where:

H = pressure gradient

μ_L = viscosity of liquid

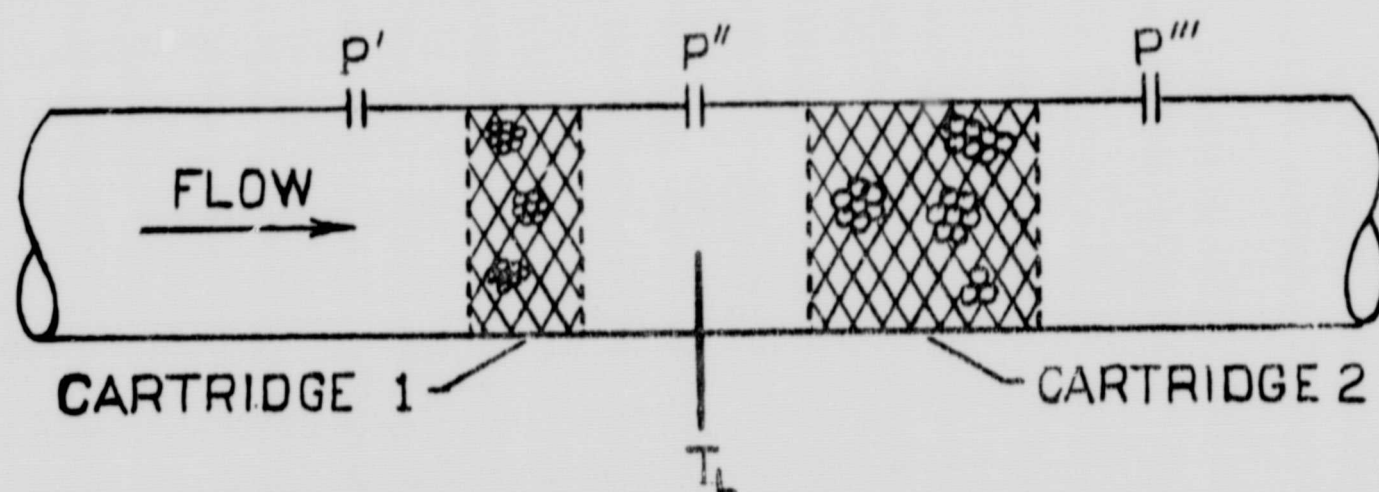


Fig. 4.5 Porous Cartridge
Two-Phase Flow Meter

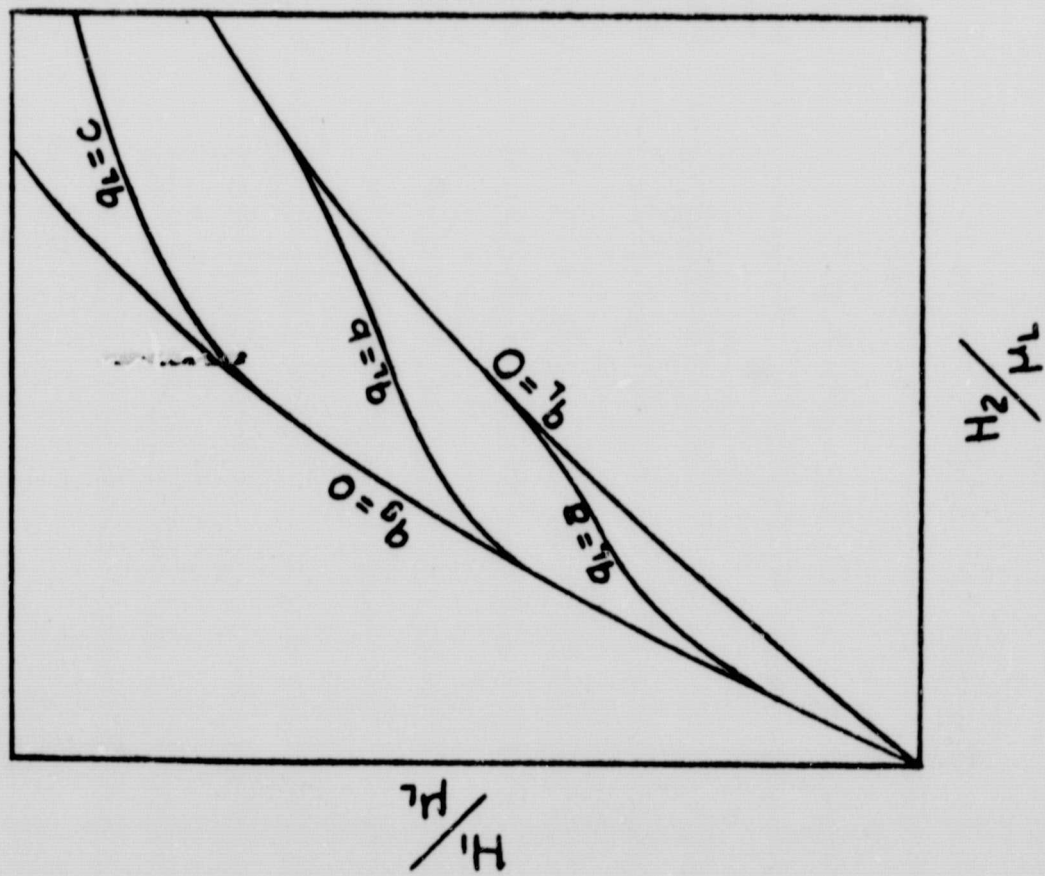


Fig. 4.6a

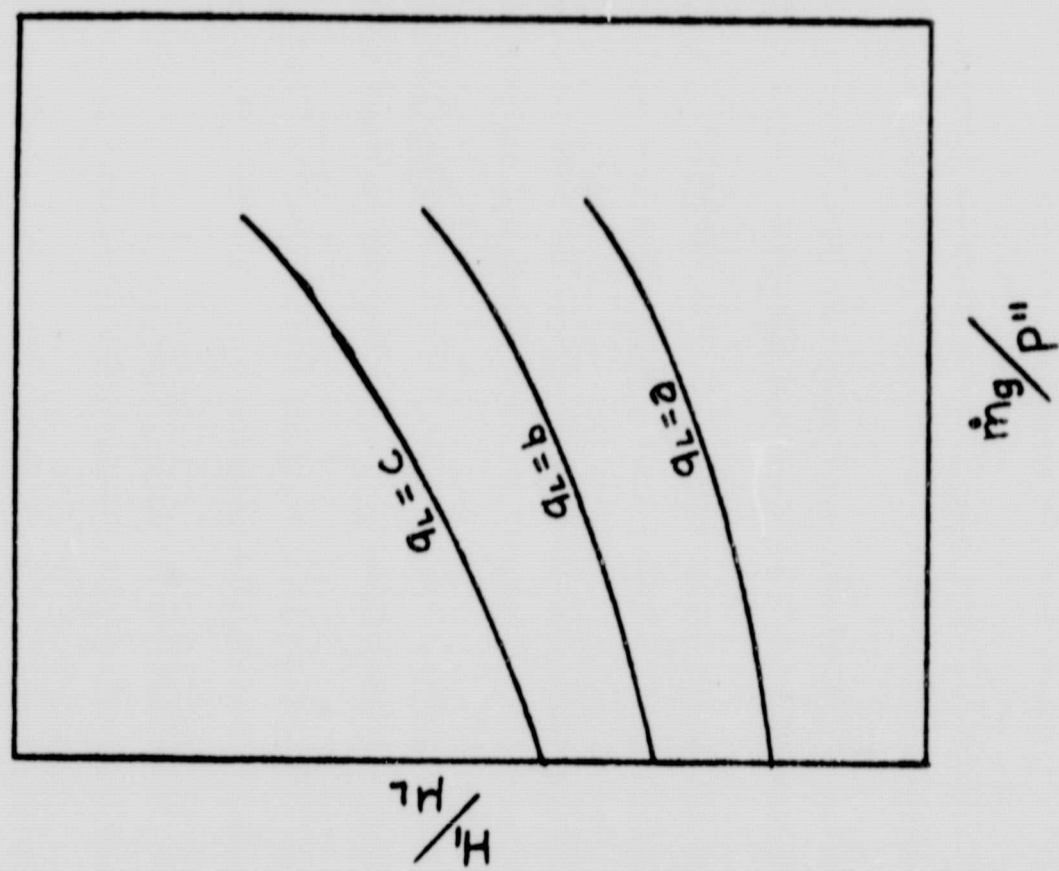


Fig. 4.6b

Fig. 4.6 Calibration Curves for the Porous Cartridge Flow Meter

q_L = liquid volumetric flow rate

$\frac{\dot{m}_g}{P}$ = gas volumetric flow rate at pressure P''

As shown in Figure 4.6a, the liquid component flow rate is specified by measurements of H_1 and H_2 , and a value for μ_L as determined by the temperature measurement. Then from the same data, the gas flow rate is specified by Figure 4.6b.

With some additional knowledge of the controlling parameters for this instrument, it is possible that porous beds already existing in a design might be calibrated for flow measurement, thus adding little if any flow resistance to the system.

4.6 Vortex Elimination

A classic problem associated with draining liquid from a container is the natural tendency for the formation of a vortex centered at the drain. The equilibrium slope of the free surface of an inviscid vortex is given by:

$$\frac{dz}{dr} = \frac{c}{gr^3}$$

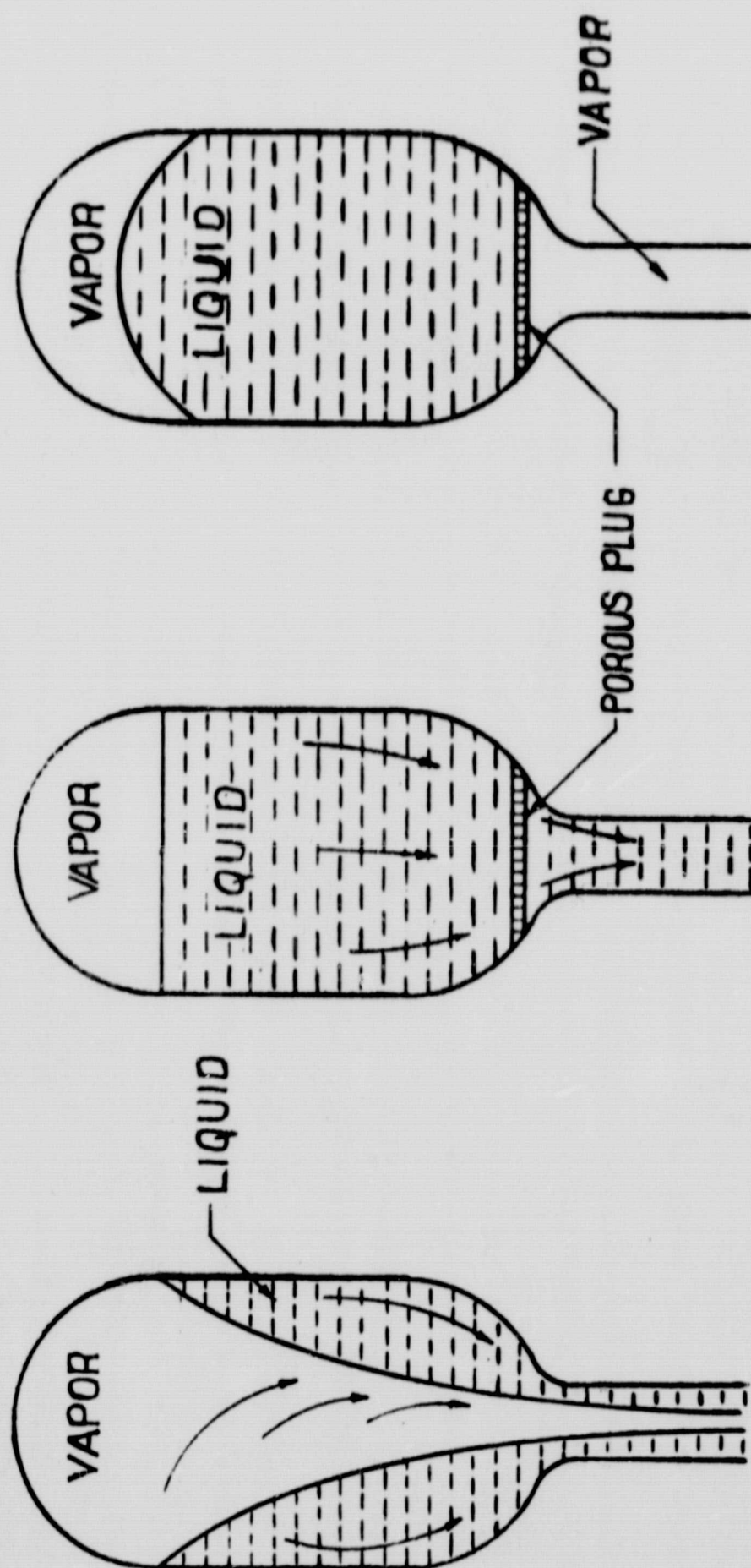
where

g = acceleration of gravity

r = distance normal to vortex axis

z = distance along vortex axis

c = constant



4.7a Draining with Vortexing and Vapor Ingestion 4.7b Vortex Elimination with a Porous Plug 4.7c Capillary Barrier Formed by Porous Plug in No-Flow Condition

Fig. 4.7 Porous Plug Effects on Tank Draining

Thus, in the absence of gravity, the slope of the free surface tends to infinity (i.e., the free surface tends to become parallel to the drain axis, see Figure 4.7a) and draining without vapor ingestion is impossible. This situation can be controlled by a honeycomb type porous plug in the vicinity of the drain; however, other undesirable effects can be introduced. In the no-flow condition the plug can form a capillary block to separate the bulk liquid in the tank from a vapor pocket in the drain line (see Figure 4.7c). Here again, a thorough understanding of the phenomena is required for design considerations.

4.7 The Fuel Cell

The fuel cell is a device that converts the chemical energy of a fuel directly to electrical energy without going through the usual combustion process. Although there are many different possible fuels, the hydrogen-oxygen cell is one of the most promising for space applications. The chemical-electrical process in this cell can be described as reverse electrolysis.

The hydrogen-oxygen cell consists of a porous anode bathed in hydrogen, a porous cathode bathed in oxygen, and an electrolyte separating the anode and cathode (see Figure 4.8). In operation, water is formed as a by-product in both porous electrodes and must be flushed from the system to avoid liquid saturation. Cell power generation is directly proportional to the quantity of fuel utilized and with an abundant supply of fuel, power generation is limited by the pore surface area in contact with the fuel gases. Thus the maximum output is limited by the nature of the two-phase flow through the porous electrodes, and the need for reliable flow prediction of both fuel components is evident.

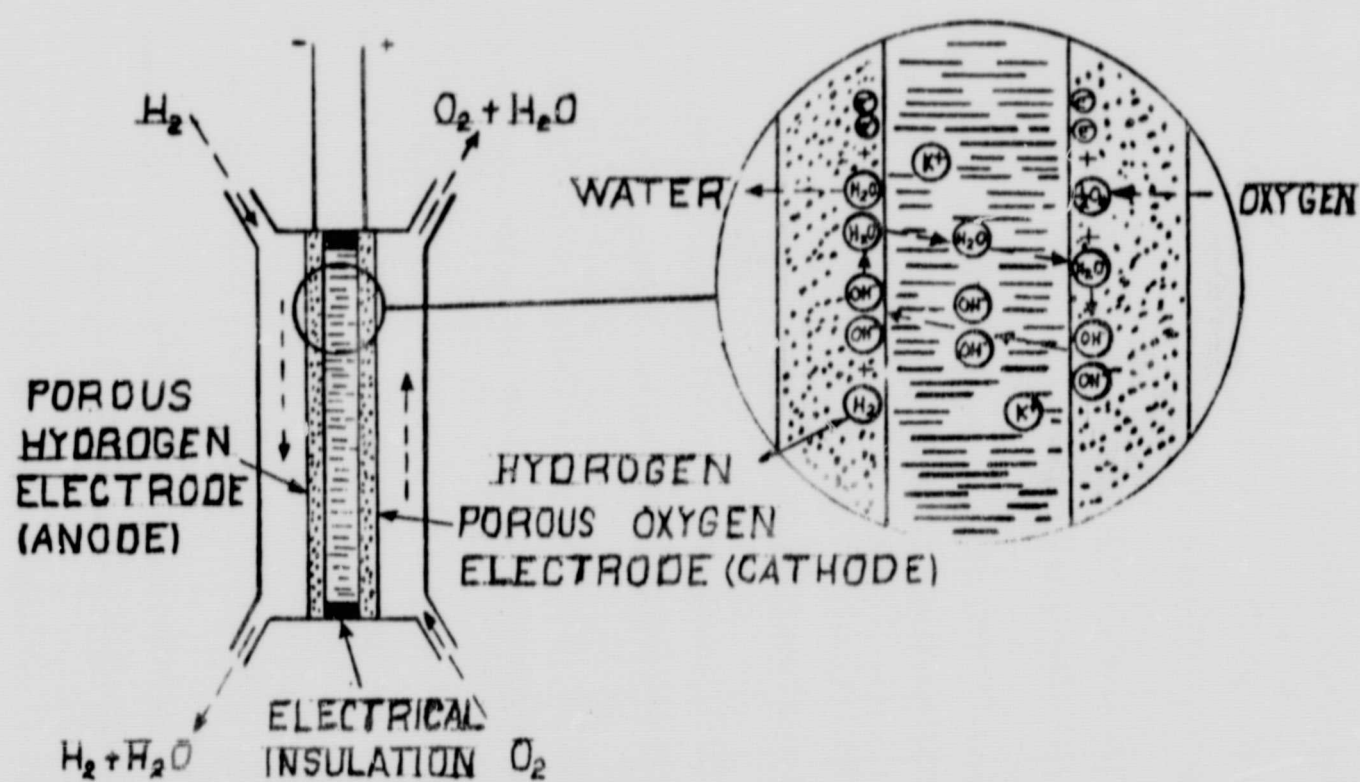


Fig. 4.8 The Hydrogen-Oxygen Fuel Cell

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