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**WATER RECYCLING SYSTEM USING
THERMOPERVAPORATION METHOD**

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ABSTRACT

A water recycling system concept for the crew of the space station is presented. A thermopervaporation method is a new key technology used for the distillation process, utilizing a hydrophobic membrane. An experimental study of thermopervaporation revealed that the permeation depends on the gap between the membrane and the cooling surface in the condensation room: the steam diffusion occurs with gaps less than 5 mm while natural convection becomes dominant with gaps more than 5 mm. A brief discussion of the system operation is also described.

1. INTRODUCTION

The manned space station will need much water for the crew activities and experiments such as those concerning life science. The cost for transportation of clean water and waste water including urine is very expensive. For example, one crew will use about 11 tons of water a year (30 l a day), which will cost about 90 million dollars just for the transportation of clean water from the ground to the space station. The introduction of the water recycling system for purification of urine and waste water will reduce the operation costs of the space station and experiments conducted in it, accordingly.

The Earth's natural recycling system is based on the natural balance of the biosphere circulation system. The biosphere activity depends on the utilization of solar energy for the circulation of air and water. In this circulation, water plays several important roles: material reservoir and transportation in state of solution or mixture; temperature control by evaporation and condensation; environmental constituents in a moisture or a liquid state. Water takes part in every material process on earth.

The enormous industrial progress and the population explosion since entering this century have revealed that the balance of the biosphere circulation system is sensitive and delicate against

external stimulants: the industrial products exhaust large amount of waste material as by-products with extremely unnatural constituents, destroying the material balance in the local ground area; the environment has, also, been destroyed by the introduction of roads in fields and mountains, by the use of agricultural chemicals and chemical fertilizer in farming, and by indiscriminate deforestation, causing an increase in desert areas. Water has also been involved in the expansion of such environmental disruption.

The movement to recover a healthy global environment has accelerated the development and manufacturing of recycling equipment/systems as well as progress in environmental science: ecological support systems have become addressed for use in the "earth" space station! Some technologies accumulated through development of recycling equipment/systems can be utilized for controlling the life support system in the space station.

The water recycling system for use in the space station can be composed of filtering processes for mid-class purification of water and a vaporation process for high purification of potable water. This corresponds to natural water recycling: the underground water or well water is purified by filtering through sands and soils; water from rivers originates in rainwater which is distilled water evaporated from the earth surface. Water used in cities, however, is mainly artificially filtrated and treated with disinfectant.

In applying the water recycling system to the space station there are many technical difficulties that arise principally from the micro-gravity condition and, the construction of a complete recycling system. The system must have the capability of preventing the mixture of gases, which degrades the system performance.

The water recycling system for the space station must be built by means of artificial technology because biotechnology still contains unknown factors, such as, hazardous effects caused under microgravity, and is lower in controllability and versatility. Moreover, limited space and limited power supplied in the space station requires small sized and low power dissipating hardware.

Other candidate systems for the space station use are summarized by Herrala, et al.⁽¹⁾, and in Japan's CELSS study, a conceptual study on the water recycling system has been reported⁽²⁾ ⁽³⁾. In our report, a candidate system configuration of the water recycling for crew usage is presented. The system presented here consists of filtration and evaporation processes, with membranes used for both types. Experimental studies on the new key technology of membrane evaporation, "thermopervaporation", using a hydrophobic membrane are introduced.

The thermopervaporation method is, essentially, favorable to use in the space station because it includes no moving parts in the basic process.

2. STUDY ON WATER RECYCLING SYSTEMS

The amount of waters treated by a one-man crew in the space station is estimated in Table 1. The most recent membrane separation performance is characterized in Fig.1.

Table 1 Water Treatment per One-Man Crew

Intake: H ₂ O	3,050 g/day	(*)
Urine	1,553 g/day	(*)
Other	1,497 g/day	(*)
Shower	10 ~ 20 ℓ a shower	

(*) Metabolism estimated by Jackson

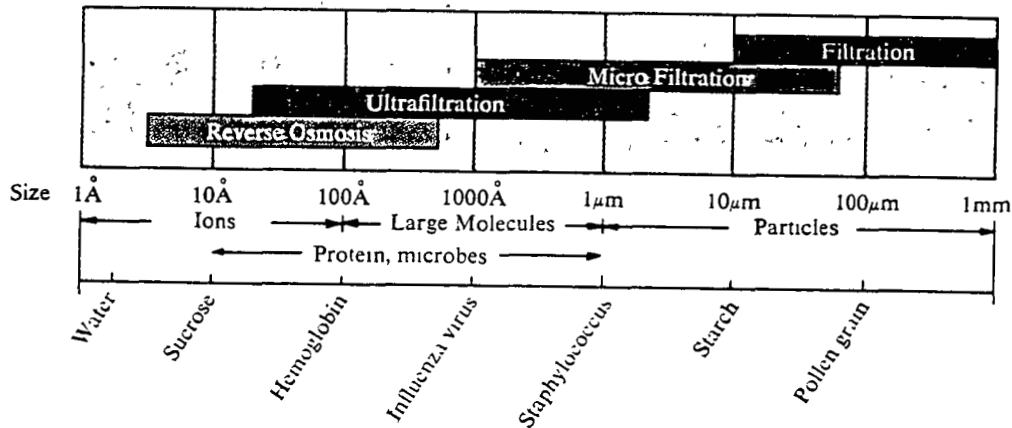


Fig. 1 Useful Ranges of Various Separation Processes

Fig.2 shows one candidate water recycling system, treating shower waste, urine, and other drainage to get shower water and potable water. First, the prefilter (micro filtration), rejects miscellaneous particles contained in the shower waste and the urine. Next, the ultrafiltration membrane rejects organic macromolecules and suspended solids, and the various solvent ions are then rejected in the reverse osmosis process. The product water from the reverse osmosis membrane is further purified by removing a trace of organic materials by means of activated charcoal, then is stored in the ultraviolet sterilization reservoir to be supplied as shower water. A portion of the permeate from the reverse osmosis membrane module is further purified by the thermopervaporation process to supply for potable water. Since the drain from the shower room includes surfactants, the feed for the thermopervaporation process is taken from the product water from the reverse osmosis membrane to prevent the membrane from losing its hydrophobic characteristic.

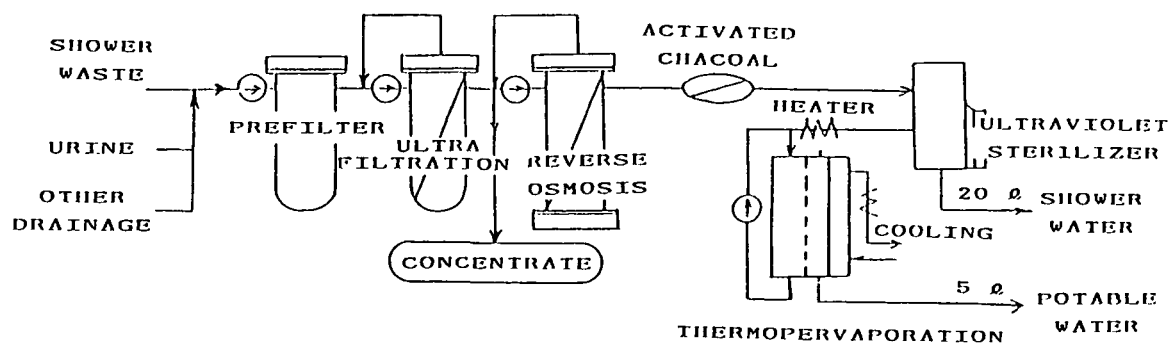


Fig. 2 Water Recycling System

This and candidate systems are shown in Table 2, and are compared and evaluated in Table 3 (system A is the one in Fig.2). The water recovery of system A is not high because the concentrate from the reverse osmosis membrane is exhausted and cannot be applied again in the recycling process. System B consists mainly of the thermopervaporation method with a crystallizer for separating solids, which results in the highest recovery, although it has the disadvantage of using more dissipation power than the other systems. Since the thermopervaporation method can use heat directly as evaporation energy, heat exhausted from various equipment in the space station can be used as the heat source and a highly reliable system is expected owing to the smaller number of components. System C is a modified configuration of system A, which includes the crystallizer to separate solids from the concentrate, and therefore realizes the highest recovery of water. The selection of system A or C depends mainly on permissible power consumption. System A is preferable from the viewpoint of the low power consumption while system C is with regard to complete water recovery. One possible treatment of the concentrate from the membrane processing is to be treated as part of the waste management system.

Table 2. Case Study of Water Recycling System

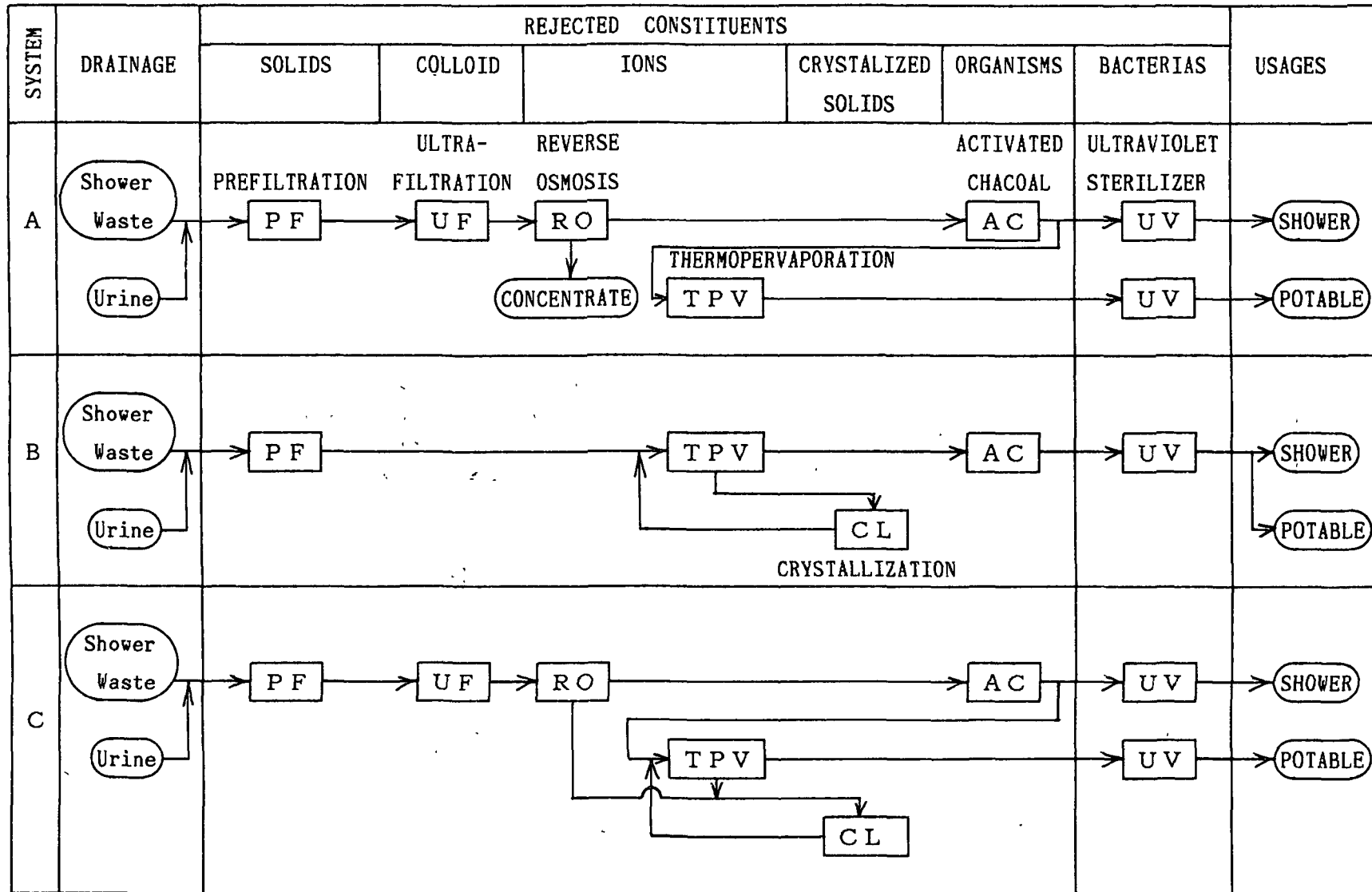


Table 3 System Comparison and Evaluation

ITEMS	SYSTEM A	SYSTEM B	SYSTEM C
WATER RECOVERY RATE (%)	80	100	100
PUMP POWER RATIO	40	1	40
T P V POWER CONSUMPTION RATIO	1	5	1
C L POWER CONSUMPTION RATIO	0	5	1
COMPONENTS NUMBER	7	5	8
FEATURES	<ul style="list-style-type: none"> • Low recovery • Low power 	<ul style="list-style-type: none"> • Small scale • Large power 	<ul style="list-style-type: none"> • Large scale • Medium power

3. THERMOPERVAPORATION TECHNOLOGY

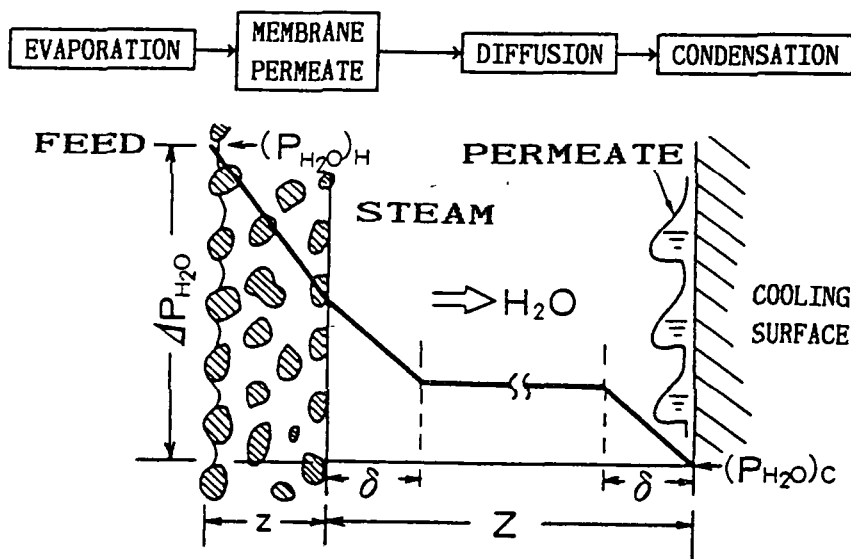
3.1 Principle and Features

The thermopervaporation method, a specialized pervaporation, is for membrane separation accompanied with phase transition. It has, however, several different features from usual pervaporation, since the porous hydrophobic membrane is used as the separation membrane. That is, the membrane has highly permeable water flux owing to its large porosity so that the ideal separation speed at a practical level is obtainable with a small temperature differential. In other words, since low-grade energy such as exhausted heat can be used as the energy source, an economical system is realizable despite the increase in consumed energy accompanied by the phase transition. Furthermore, by the multiplicative effect of vaporization and membrane separation, the separation ratio of solvents is expected to be extremely high, over 99.99 %. Since the membrane is fabricated, in general, from polytetrafluoroethylene (PTFE), it possesses excellent resistance to heat, chemicals and pH, compared with previous reverse osmosis membranes.

Table 4 shows the features of the thermopervaporation method in comparison with the vacuum pervaporation method. The feed coming into contact with the membrane vaporizes at the membrane surface. The generated vapor passes through pores of the membrane surface,

Table 4 Features of Thermopervaporation

		THERMOPERVAPORATION	PERVAPORATION
PRINCIPLE	MODEL		
	MECHANISM	EVAPORATION → PERMEATION	PERMEATION → EVAPORATION
	DRIVING FORCE	TEMPERATURE (STEAM PRESSURE) DIFFERENCE	PRESSURE DIFFERENCE
MEMBRANE	MATERIAL	HYDROPHOBIC	HYDROPHILIC
	STRUCTURE	POROUS	NON POROUS
OPERATION PRESSURE		NORMAL PRESSURE	EVACUATION
OPERATION TEMPERATURE		< BOILING POINT	ROOM TEMPERATURE



$$\Delta P_{H_2O} = (P_{H_2O})_H - (P_{H_2O})_C \text{ VAPOR PRESSURE DIFFERENTIAL}$$

- | | |
|-----------------------------------|--|
| ϵ MEMBRANE POROSITY | D_M DIFFUSION COEFFICIENT IN THE MEMBRANE |
| R GAS CONSTANT | D_G DIFFUSION COEFFICIENT OF GASEOUS PHASE |
| z MEMBRANE THICKNESS | Z GAP (TRANSFER DISTANCE) |
| δ BOUNDARY LAYER THICKNESS | |
| T TEMPERATURE | |

Fig. 3 Membrane Separation Model of Thermopervaporation

diffuses to reach the cooling surface, where it is condensed. The driving force of the membrane permeate depends on the differential between the vapor content on the membrane surface and that on the cooling surface. The content differential is produced by the temperature differential of the feed and the permeate as shown in Fig.3, which illustrates a membrane separation model of thermopervaporation. Thermopervaporation, with its principles and features as stated above, offers wide applications such as the seawater desalting⁽⁴⁾ ⁽⁵⁾, and the concentration of acids and alkalis⁽⁶⁾, while research on the separation mechanism has continued.⁽⁷⁾ ⁽⁸⁾ In the following sections, experiments on thermopervaporation are described.

3.2 Experimental Method

Fig.4 shows the flow of the experimental system. The membrane separation cell is composed of an evaporation room, a condensation room, and a cooling room in a layer structure using the hydrophobic membrane and the cooling surface. The hydrophobic membrane used is fabricated of PTFE (Nitto Electric Industrial Co., Ltd.) with a mean pore size of 0.05 ~ 2.0 μm and an effective membrane area of $148 \times 10^{-2} \text{ m}^2$ (Table 5). The feed is heated to a specified temperature and sent to the evaporation room by the feed pump. The cooling water, which is cooled at a specified temperature, is circulated by the cooling water pump. The steam, which is

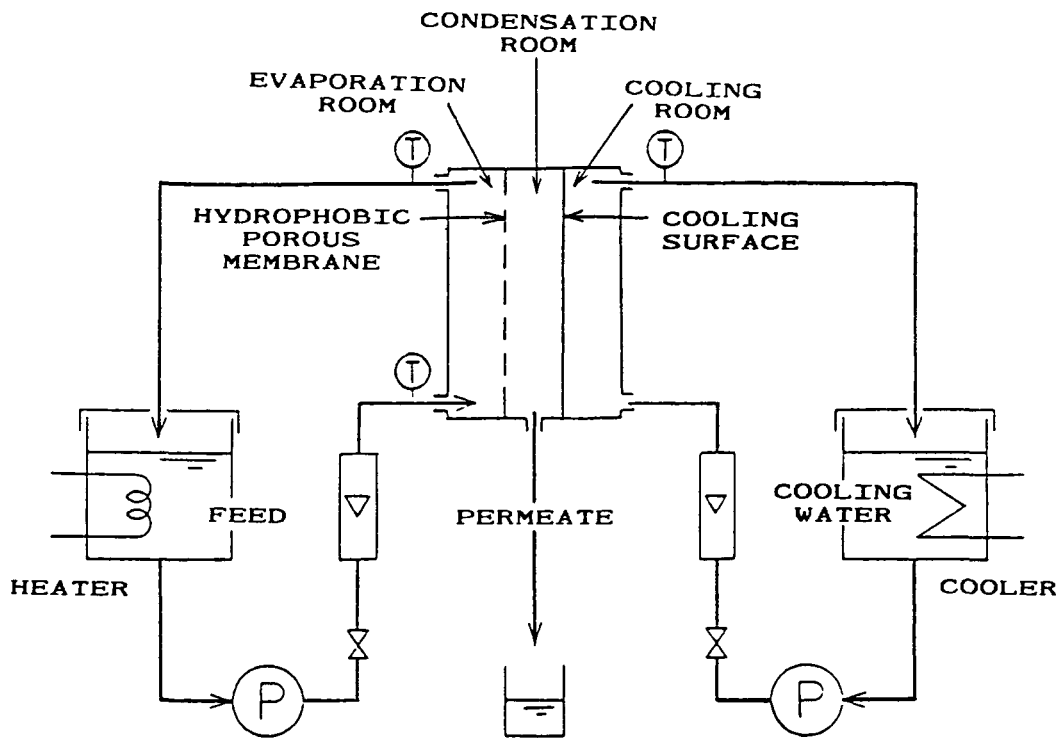


Fig. 4 Experimental Flow

Table 5 Porosity of PTFE Membrane (*)

PORE SIZE (μm)	MEMBRANE THICKNESS (μm)	POROSITY
2.00	83	0.84
0.15	70	0.72
0.05	89	0.64

(*) Fabricated by Nitto Electric Industrial Co., Ltd.

evaporated on the inner surface of the membrane in the evaporation room and passed through the membrane, is condensed on the cooling surface and then collected in a beaker for measurement.

The experimental study was performed under the following conditions for confirming the steam permeation mechanism of the thermopervaporation method and clarify factors affecting the membrane separation performance:

- (1) Temperature of feed: 30 ~ 60 °C
- (2) Temperature of cooling water: 7 °C
- (3) Membrane pore size: 0.05 ~ 2.0 μm
- (4) Gap between membrane and cooling surface: 0.8 ~ 25.3 mm

3.3 Experimental Results

3.3.1 Permeation performance and water quality

Fig.5 shows the separation characteristic of the NaCl aqueous solution and the water quality of obtained permeate represented by the electric conductivity. The permeate water flux Q is proportional to the saturated vapor pressure differential ΔP between the feed and the cooled permeate water. The water quality of the permeate is below 5 $\mu\text{S}/\text{cm}$, independent of the vapor pressure, compared with the feed electric conductivity of 49 mS/cm ,

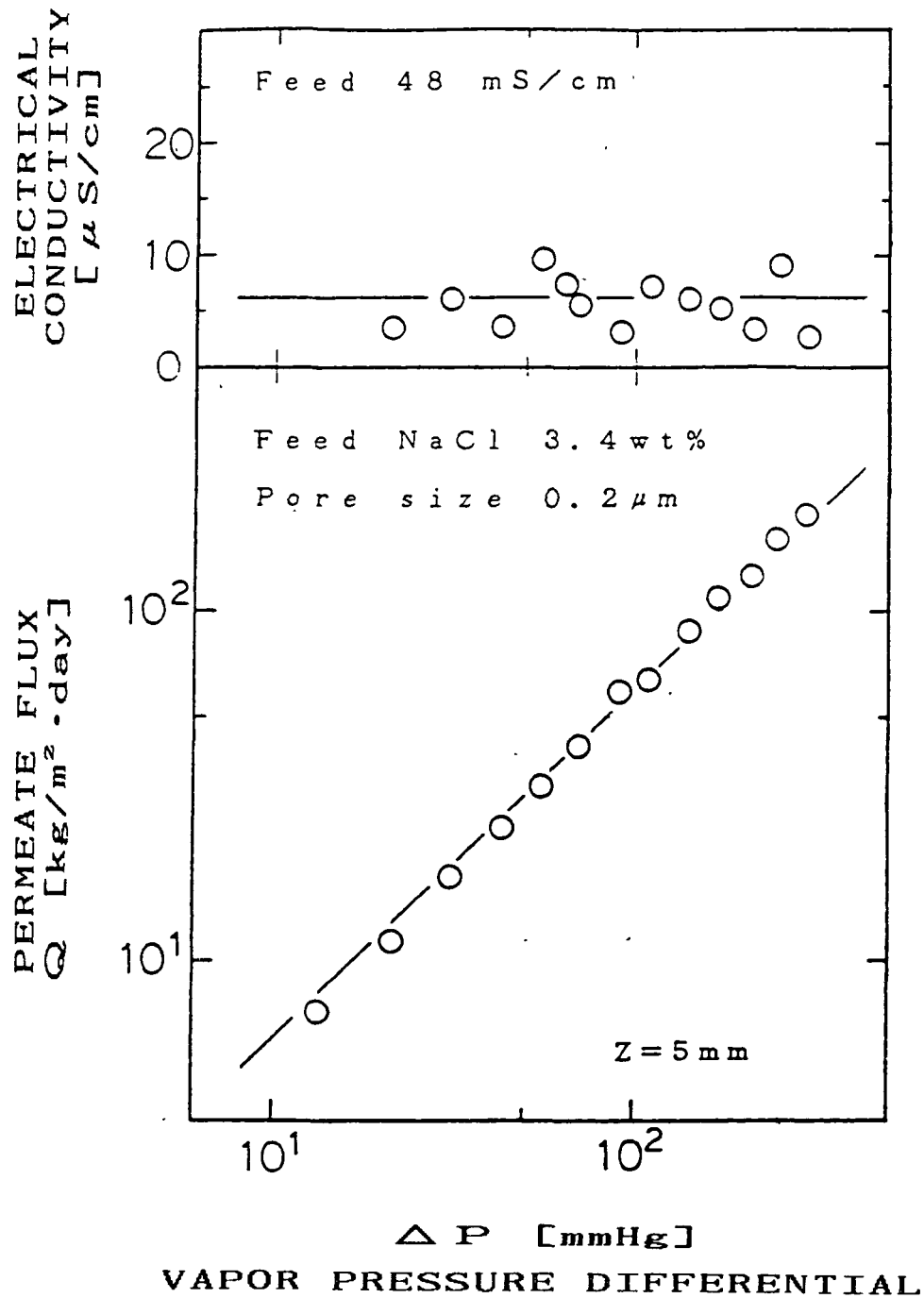


Fig. 5 Separation Characteristic of Water Quality of NaCl Aqueous Solution When Permeated through Thermopervaporation

the product water being ultrapure with the saline rejection of over 99.99 %.

3.3.2 Effect of gap between membrane and cooling surface

Fig.6 shows the relationship of the vapor pressure differential ΔP and the permeate flux Q , when the gap Z between the membrane and the cooling surface is varied. With any gap size the permeate flux is proportional to the vapor pressure differential with a tendency similar to that in Fig. 3: with gaps of less than 5.3 mm the permeate flux increases as the gap becomes small, and with gaps of more than 10.3 mm the permeate flux demonstrates almost no change. We have determined that the permeate mechanism changes with a gap around 5 mm.

3.3.3 Investigation of permeate mechanism

Using the experimental data in Fig.6, the relation of the gap Z and the permeation factor K was obtained as shown in Fig.7, where the permeation factor K is defined by Eq.(1).

$$K = \frac{Q}{\Delta P} \quad (\text{kg/m}^2 \cdot \text{day} \cdot \text{mmHg}) \quad (1)$$

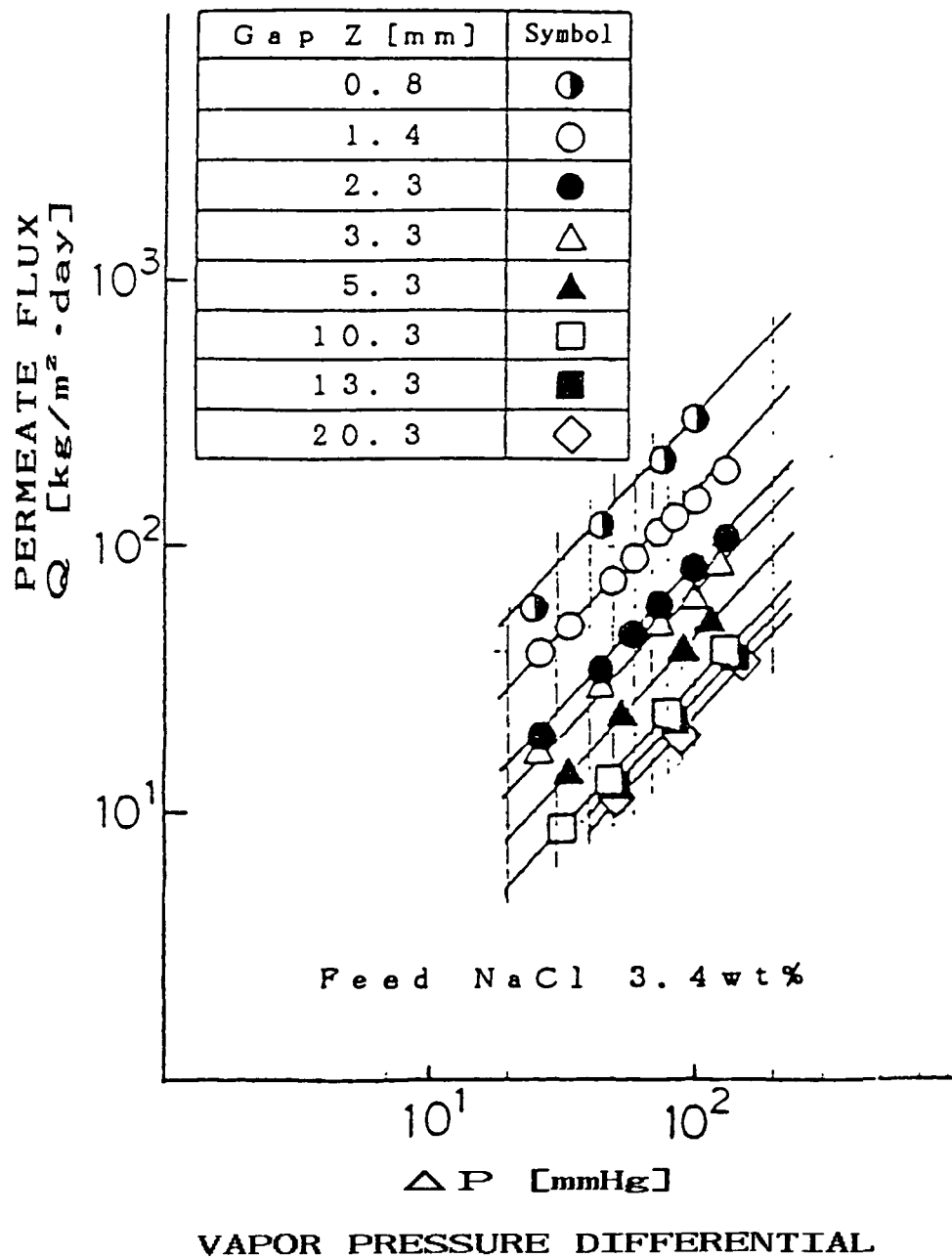


Fig. 6 Effect of Gap on Permeate Flux

(REMARK) D: Diffusion coefficient (m²/day)
 π: Total pressure (mmHg)
 T: Mean temperature (°K)
 $\overline{P_{air}}$: Logarithmic mean partial air pressure

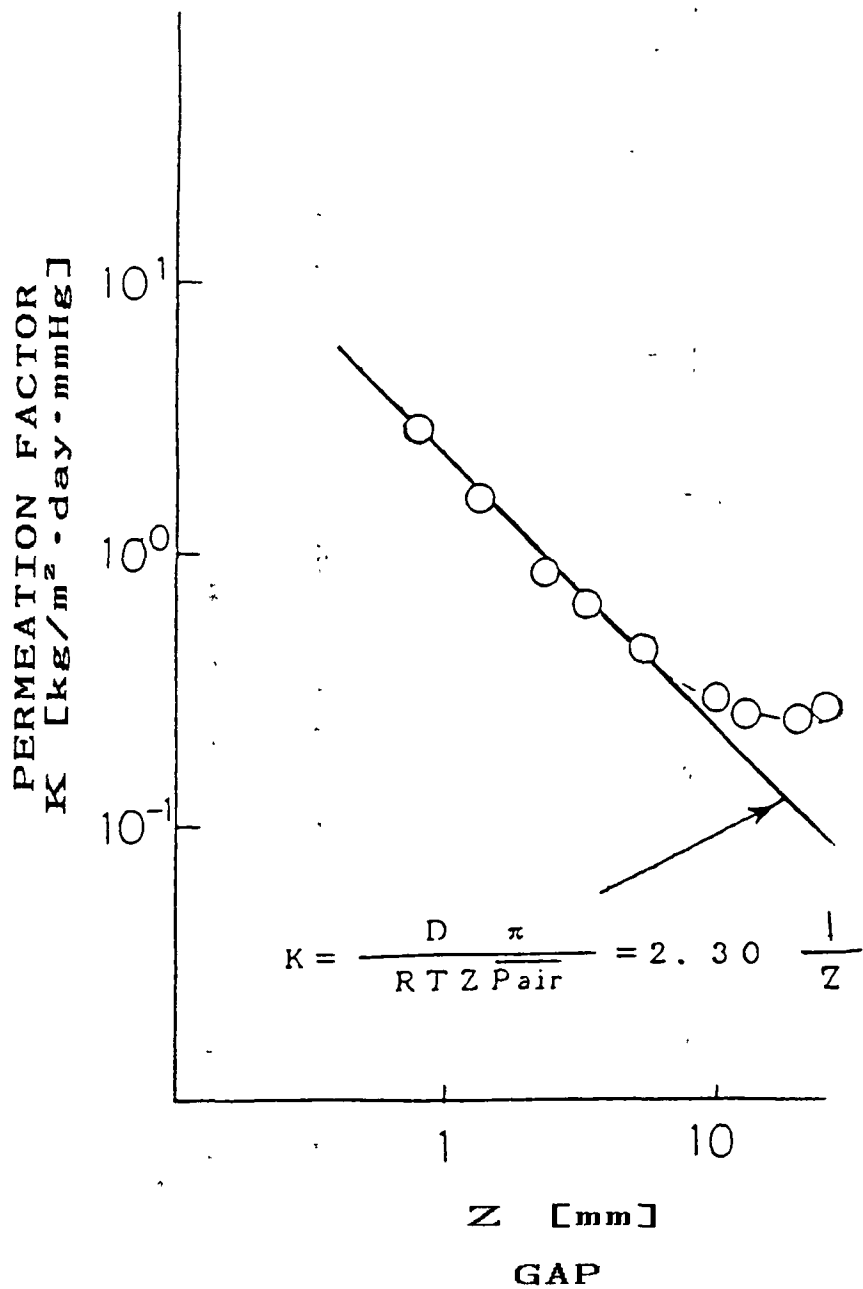


Fig. 7 Effect of GAP on Permeation Factor

As a result, with gaps below 5 mm the permeation factor is proportional to the minus first order of the gap, and the permeation factor shifts off the line of the minus first order and then becomes constant with gaps over 5 mm. In other words, the permeation factor is inversely proportional to gaps less than 5 mm but is not influenced with gaps more than 5 mm. From this, it is deduced that with gaps less than 5 mm, the permeate water flux depends on the steam diffusion in the condensation room, and with gaps more than 5 mm, on the natural convection produced in the condensation room to cause the vapor transfer.

With gaps below 5 mm, we computed the quantity of the steam diffusing in the condensation room by using the diffusion equation. Since air in the condensation room can be postulated to be stationary, we can treat it as unilateral diffusion.

The steam travel speed Q' can be represented as :

$$Q' = \frac{D \cdot \pi}{R T Z \overline{P_{air}}} \cdot \Delta P, \quad (2)$$

where D is the diffusion coefficient (m^2/day), π the total pressure (mmHg), T the mean temperature ($^{\circ}K$), and $\overline{P_{air}}$ the logarithmic mean partial air pressure (mmHg).

Consequently, the permeation factor K is expressed as :

$$K = \frac{Q'}{\Delta P} = \frac{D \cdot \pi}{R T Z \bar{P}_{air}} \quad (3)$$

Using parameters under the present condition, Eq.(3) is simply modified into:

$$K = 2.30 \cdot \frac{1}{Z} \quad (4)$$

In this modification, the temperature dependency of the diffusion coefficient D is obtained as Eq.(5) by plotting the results⁽³⁾ of E.N. Fuller, et al.

$$D' = 1.4 \times 10^{-3} \cdot T' + 0.22, \quad (5)$$

where D' is the diffusion coefficient (cm²/sec), and T' the temperature (°C).

The solid line in Fig.5 shows the calculated relation (Eq.(4)) of the gap and the permeation factor. From this, we found that a close agreement between Eq.(4) and experimental results with gaps less than 5 mm and the permeation factor, namely the permeate water flux, agrees with the diffusing steam quantity in the condensation room.

From the results of the thermopervaporation experiment that was carried out on the ground as stated above, we can conclude that while the mass transfer of the steam is determined by the natural convection in the condensation room with gaps above 5 mm, it is determined by the steam diffusion speed in the condensation room with gaps less than 5 mm.

From this experimental data, the permeate flux Q is expressed as:

$$Q \propto \frac{\Delta P_{H_2O}}{R T \left(\frac{z}{D_M \cdot \epsilon} + \frac{2 \delta}{D_G} \right)}, \quad (6)$$

MEMBRANE
GASEOUS
RESISTANCE
RESISTANCE

where $\Delta P_{H_2O} = (P_{H_2O})_H - (P_{H_2O})_C$ is the vapor pressure differential, R the gas constant, T the temperature, Z the membrane thickness, D_M the diffusion coefficient in the membrane, ϵ the membrane porosity, δ the boundary layer thickness, and D_G the diffusion coefficient of gaseous phase, as shown in Fig.3.

However, since it is said that the natural convection, in general, does not occur under zero gravity, the permeation dominated by the steam diffusion should be expected irrespective of the gap between

the membrane and the cooling surface in the condensation room. As a result, with gaps more than 5 mm, efficiency of the evaporation using the thermopervaporation method in space becomes lower than in the ground, because the permeation factor is inversely proportional to the gap as expressed in Eq.(4).

4. CONCLUSIONS

The restricted utility resources usable in the space station demand on compact hardware and low consumption power as well as reliability. If a shower system with low water utilization in the space station can be developed, compact and low power consuming equipment can be easily constructed.

The thermopervaporation method enables the use of low quality energy, such as exhausted heat from other equipment, as the evaporation energy. Thus, one possibility is to use exhausted heat from the gas recycle equipment which may be installed next to the water recycling equipment. The serial operation of each step of membrane processing, like interlock circuits, reduces the operating peak power, which is suitable for adhering to safety requirements.

Another water recycling system⁽¹⁰⁾ to be applied to the Japan's experimental module will be used for life science experiments.

The system scale is similar to that presented here, but with a relatively different configuration due to the different constituents which contain no surfactants. The system configuration presented here is usable for Japan's experimental module.

An experimental study on thermopervaporation was made on the ground. In this experiment, the condensation room in the thermopervaporation cell is filled with air, but as an alternate application for space, the condensation room contains only steam to avoid mixture with air during the post process. Moreover, there are still many factors to be developed: a degasing process, thermal efficiency for low power consumption, reliable small pumps, separation of concentrate, cleaning of contaminated membrane, maintenance, etc.

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