APPLICATION STUDY OF THE HEAT PIPE TO THE PASSIVE DECAY HEAT REMOVAL SYSTEM OF THE MODULAR HTR

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Abstract

To investigate the applicability of the heat pipe to the decay hat removal (DHR) system of the modular HTRs, preliminary study of the Heat Pipe DHR System was performed. The results show that the Heat Pipe DHR System is applicable to the modular HTRs and its heat removal capability is sufficient. Especially, by applying the variable conductance heat pipe, possibility of a fully passive DHR system with lower heat loss during normal operation is suggested.

The experiments to obtain the fundamental characteristics data of the variable conductance heat pipe were carried out. The experimental results show very clear features of self-control characteristics. The experimental results and the experimental analysis results are also shown.

INTRODUCTION

One of the most important features of the modular HTR is a passive decay heat removal (DHR) characteristic. It is performed by the cooling system installed outside the reactor pressure vessel. Residual heat and decay heat generated in the core is transferred to the reactor pressure vessel and then to the decay heat removal system passively by the natural phenomena such as conduction, radiation and convection.
The purpose of our study is to establish the concept of the fully passive and highly reliable decay heat removal system utilizing the separated type of heat pipe. Moreover the aim of our concept is a self-regulation characteristics to minimize the heat loss under the normal operation with maintaining the sufficient heat removal capability during the accidents.

The authors are examining the application of the heat pipe system to the DHR system expecting to have comparatively high heat removal capacity and low pressure vessel temperature without any active components.

This paper provides the outline of the preliminary study of the Heat Pipe DHR system. The experiments to obtain the fundamental characteristics data of the variable conductance heat pipe were carried out and the experimental results with the experimental analysis results are also shown.

PRELIMINARY STUDY OF HEAT PIPE DHR SYSTEM

System Concept

The concept of the Heat-Pipe DHR System is shown in Fig. 1.

The separated type of heat pipe is suitable for DHR system because of its large heat removal capacity. It consists of four parts, i.e., pipe for vapor, pipe for liquid, the evaporator part and the condenser part. The evaporator part is installed on the reactor cavity wall. Decay heat of the core is transferred from the reactor pressure vessel to the evaporator part by radiation and natural convection in the reactor cavity. In the evaporator part, the heat from the reactor pressure vessel is changed into the latent heat of the working fluid and flow to the condenser part outside of the reactor building. The condenser part comprises heat exchanging pipes cooled by the atmospheric air through natural convection strengthened by the stack. Decay heat of the core is transferred to the atmosphere in this condenser part and condensed working fluid returns to the evaporator part by the gravity.

To improve the advantages of the Heat Pipe DHR System, an introduction of Variable Conductance Heat Pipe (VCHP) was investigated. Basic principle of VCHP is adding a quantity of non-condensable gas into the system for controlling the system working temperature at the intended temperature level. By adjusting the amount of the non-condensable gas in the system, the volume of the surge tank connected to the condenser, as shown in Fig.1, or the gas pressure initially enclosed into the system, it can be designed that the heat loss during the normal operation can be reduced with maintaining the maximum heat removal rate under accident.

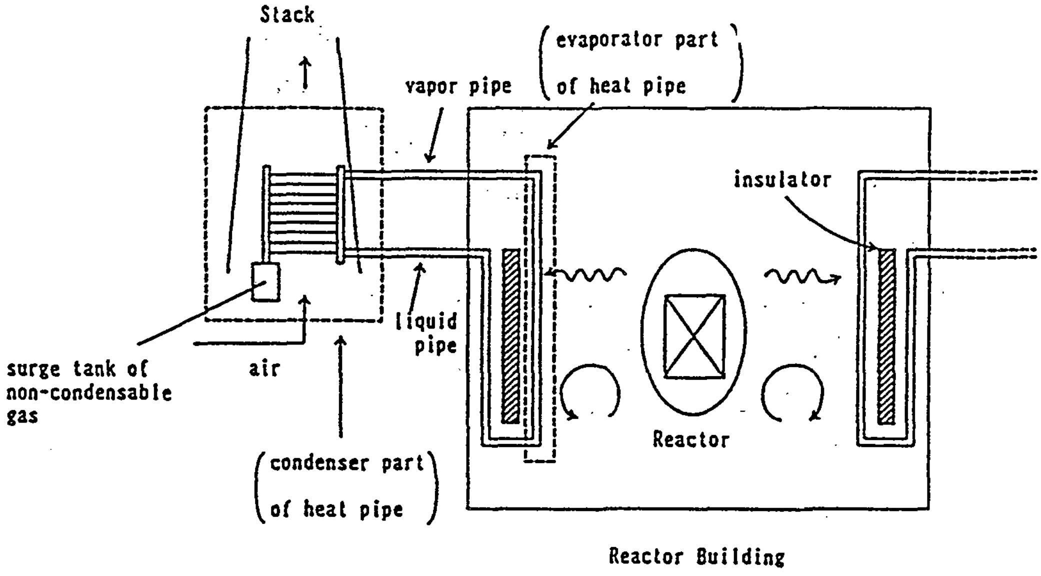

Fig.1. Concept of Variable Conductance Heat Pipe (VCHP) Decay Heat Removal System for Modular HTR

No active components are used in the system and the core decay heat is removed by fully passive measures.

Temperature Distribution Analysis under Depressurization Accident

Temperature distribution analyses of the reactor with heat pipe DHR system under the normal operating condition and the depressurization accident were performed. 350MWth MHTGR is taken as a reference reactor here.

Computer program and analytical model

Computer program used in the analysis is TAC-2D which is a two dimensional heat transfer calculation program using the finite difference method.[4] The reactor and the decay heat removal system outside of the reactor vessel were modeled in a r-z cylindrical configuration as shown in Fig. 2. The structures above the upper reflector and below the lower reflector were neglected and the top of the upper reflector and the bottom of the lower reflector were modeled as adiabatic boundaries for simplicity. This simplification does not have much effect on the estimation of the maximum core temperature and the maximum reactor vessel temperature.

The active core was modeled into one homogeneous material, which has an equivalent thermal conductivity and heat capacity of the fuel block. The decay heat was calculated with Sure's equation.

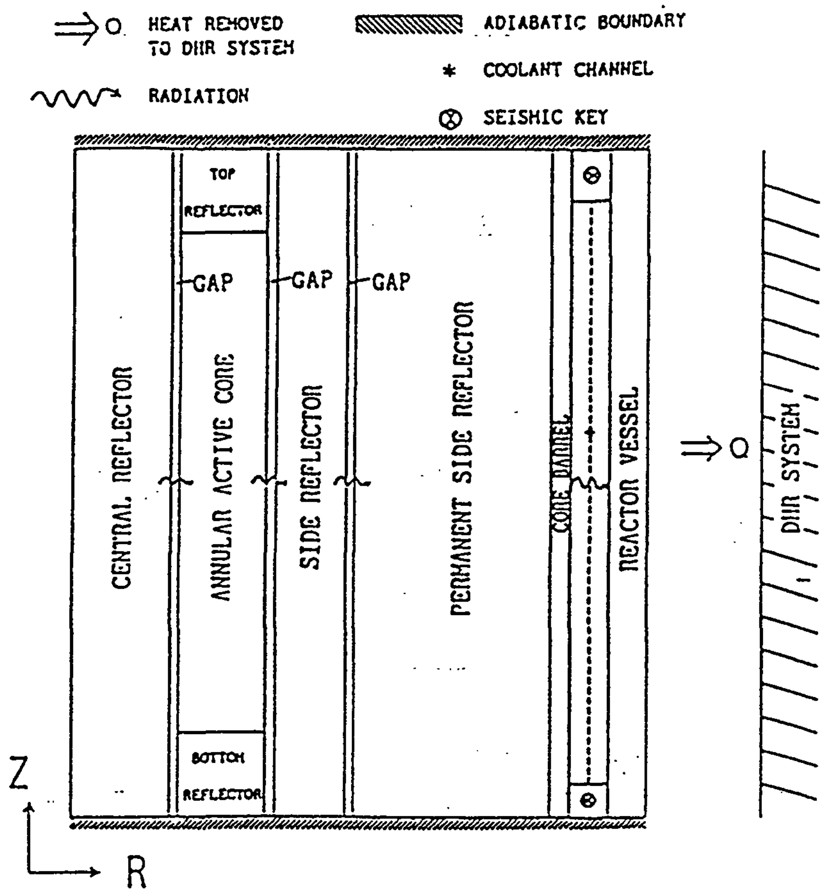

Fig.2. Analytical model for the temperature Distribution calculation

Analytical model for Heat Pipe DHR System

The heat removal characteristics of the Heat Pipe DHR System previously derived as a function of the reactor vessel temperature were modeled as a boundary condition outside the reactor vessel.

Initial condition

The core temperature distribution under the normal operation were previously calculated with an adiabatic single channel model for each radial region of the core. Then the temperature of the reactor vessel and the other reactor internals were calculated with the reactor model shown in Fig.. 2 under the boundary condition of the core temperature distribution derived above.

Results of the transient temperature calculation

The calculation results of the transient temperature under the depressurization accident are shown in Fig.3.

After loss of primary system pressure and forced cooling from full power operation, the core temperature begins to increase. The temperature of RPV and DHR system under normal operating condition are 203℃ and 61℃, respectively. The heat loss during the normal operation is 560 kW, which is lower than the case of the ordinary heat pipe system. The maximum core temperature during accident reaches to 1399 ℃ and the maximum reactor vessel temperature is 415℃, which are well below than the safety limits.

The advantage of the proposed system is to be capable of selecting the preferable working temperature with consideration on both the normal condition and accident condition. In this study, the working temperature at 100 ℃, for example, is selected.

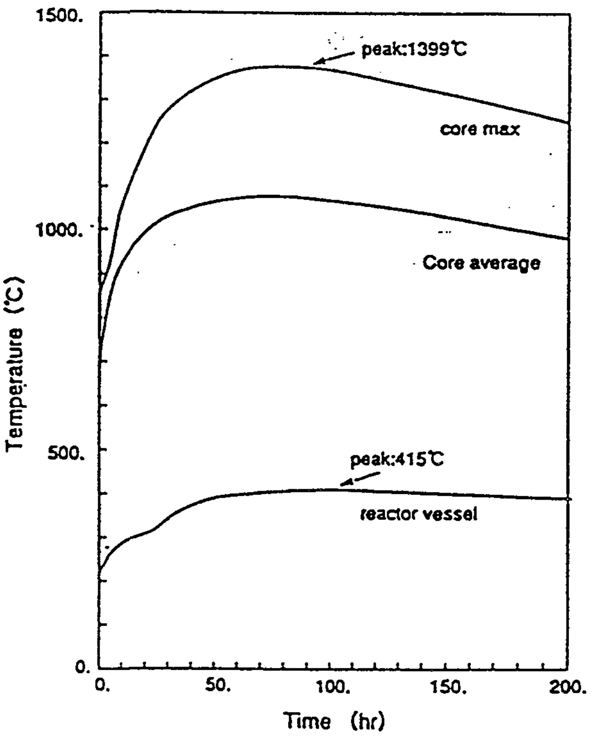

Fig.3. Temperature Behavior under Depressurization Accident

EXPERIMENTS

Experimental Apparatus

To confirm the fundamental characteristics of the VCHP, we have conducted a series of experiments with three experimental apparatuses which are (1) horizontal condenser type with forced air cooling, (2) vertical condenser type with forced air cooling and (3) vertical condenser type with water pool natural cooling. These results are already reported in the previous paper.$^{5)}$

As the cooling condition of the third apparatus are not clear, we have prepared a new apparatus with forced water cooling, which is shown in Fig.4. Nitrogen gas was fed from N_2 gas bomb through a reducing valve at an intended pressure level. The system was also capable of being vacuums by a rotary pump. The heat was supplied by a sheathed heater fixed around the evaporator covered with thermal insulation and was controlled by the voltage regulator.

Experimental Results

Nitrogen gas was used for the non-condensable gas and water or methanol was used as working fluid. The temperature distributions in the condenser tubes were recorded by scanning a sheath thermo-couple through a thin tube enclosed in the condenser tubes. Experiments have been done under the various initial N_2 gas pressure Po and heat input Q .

Fig.5 shows temperature distribution behaviors in the case water is used as working fluid when the heat input is varied from 300 W to 1100W on the condition without non-condensable gas initially enclosed. In this case it is characterized that the system temperature,i.e., vapor temperature inside the tube is comparatively low and the temperature distribution is flat. The temperature level of the system is increased in accordance with the increase of heat input. In this case, the condensation seems to be occurred for the whole region of the condenser tube, and consequently temperature level bocomes relatively low.

If non-condensable gas is enclosed initially, however, the temperature behaviors drastically change. Fig.6 shows the temperature distribution in the condenser tube in response to the increase of the heat input. The heat input was varied from Q=300 W to 1100W. Nitrogen gas was initially enclosed at 0.014 MPa (about 0.14 ata). Temperature in the evaporator side, that is the system temperature, is fairy increased while the temperature in the return tube side slopes down. It seems that the most part of the condensation area is filled with nitrogen gas and the condensation is limited to the area starting the temperature sloping down. When the heat input is increased, condensation area increased by itself, thus the controlling the system temperature rise. This result shows clearly the self-control features.

The steam boundary seems to automatically expand in accordance with the increase of the heat input, resulting in moderate system temperature rise.

The system temperature behaviors in response to the various heat input Q and the initial N_2 gas pressure enclosed in the case of water as working fluid are shown in Fig.7. With no N_2 gas enclosed, the system temperature increases with the increase of heat input because the system has no self-control

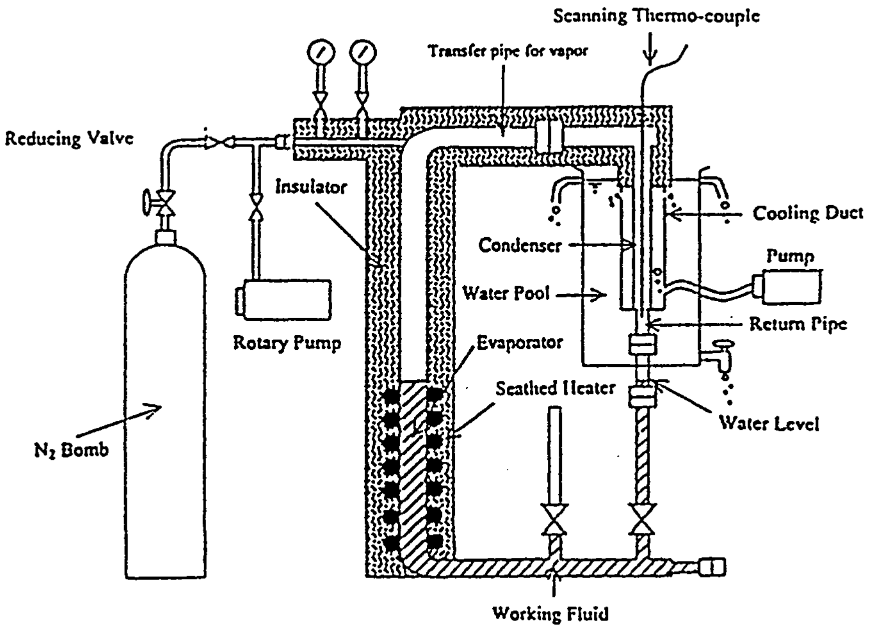

Fig.4. Experimental Apparatus

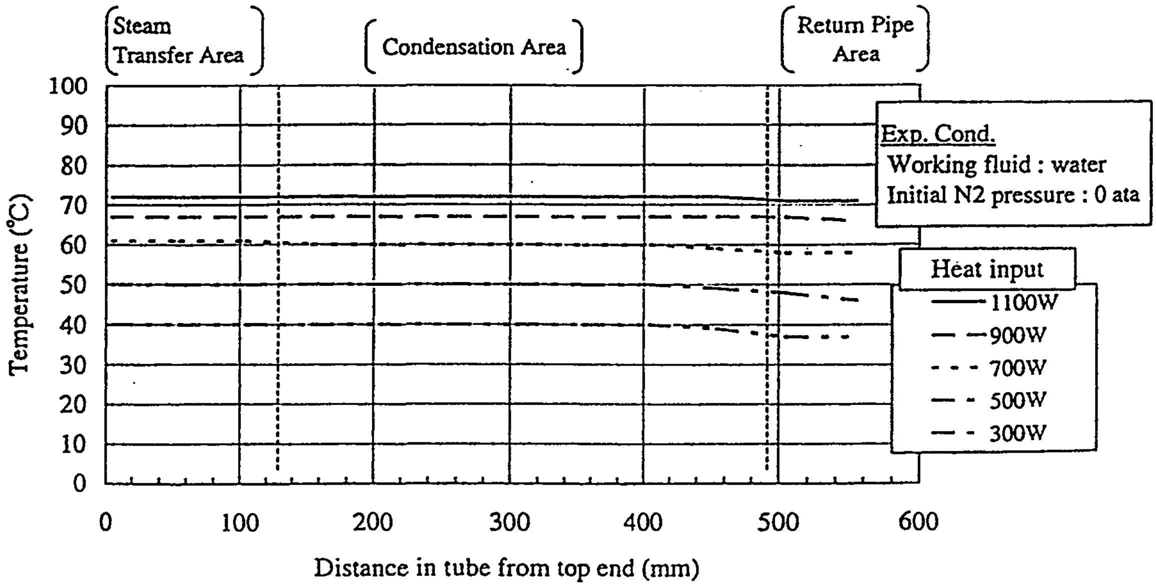

Fig.5 Temperature distribution in the tube for various heat input
in the case of "without N2 gas"

features. If non-condensable gas is enclosed, the system temperature steps up with the nitrogen gas pressure, but becomes fairly flat.

Fig.8 shows results in the case that methanol was used as working fluid. Though the system temperatures are relatively lower than the case of water, it shows similar characteristics on the water as working fluid.

These facts mentioned above means that by selection of gas and by designing the gas pressure initially enclosed the intended temperature can be achieved and the system temperature can be controlled in such a system of the separated type, variable conductance heat pipe systems.

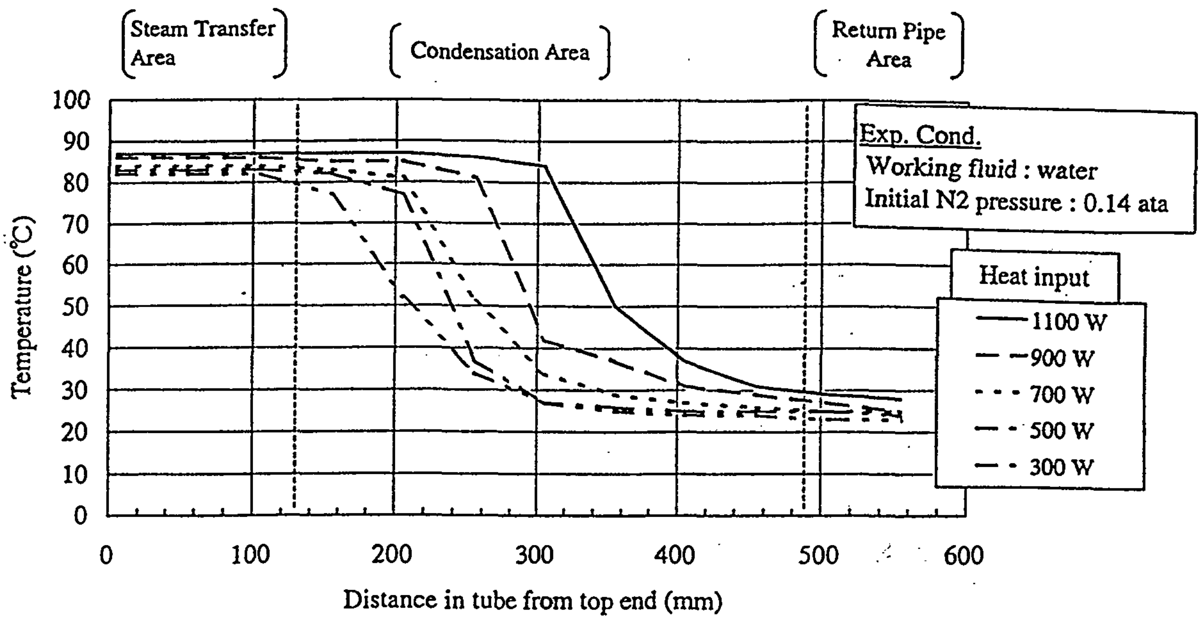

Fig.6 Temperature distribution in the tube for various heat input in the case of "N2 gas enclosed"

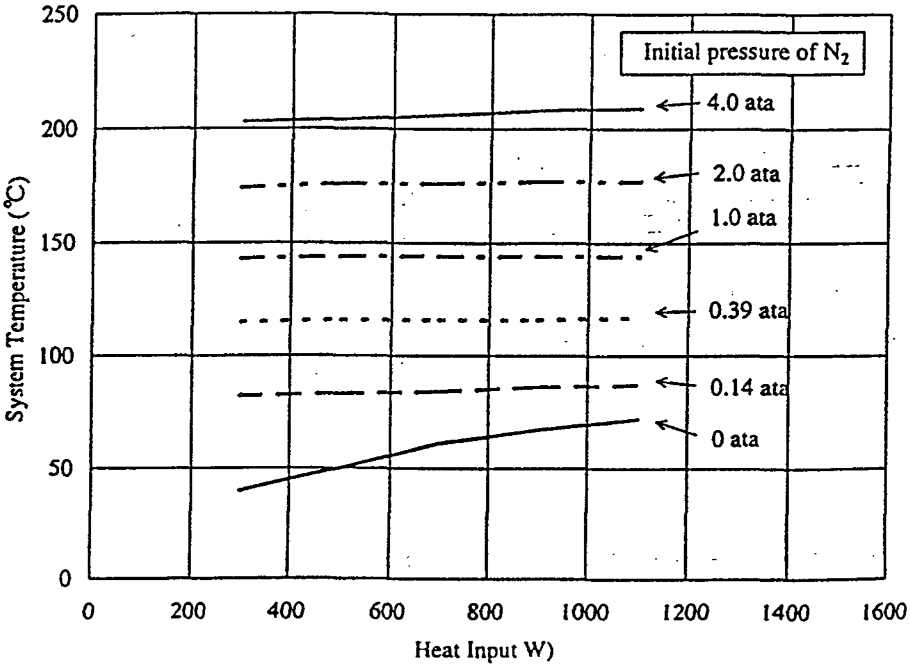

Fig.7 System Temperature Behaviors in Response to the Parametric Changes of Heat Inpu -Working fluid : Water-

Experimental Analyses

Model of self-control mechanism

The experimental results show very clear features of self-control of the system to the wide range of heat input changes. Though these facts it was confirmed that the characteristics of the self regulation behaviors are true for the heat pipe system of separate type.

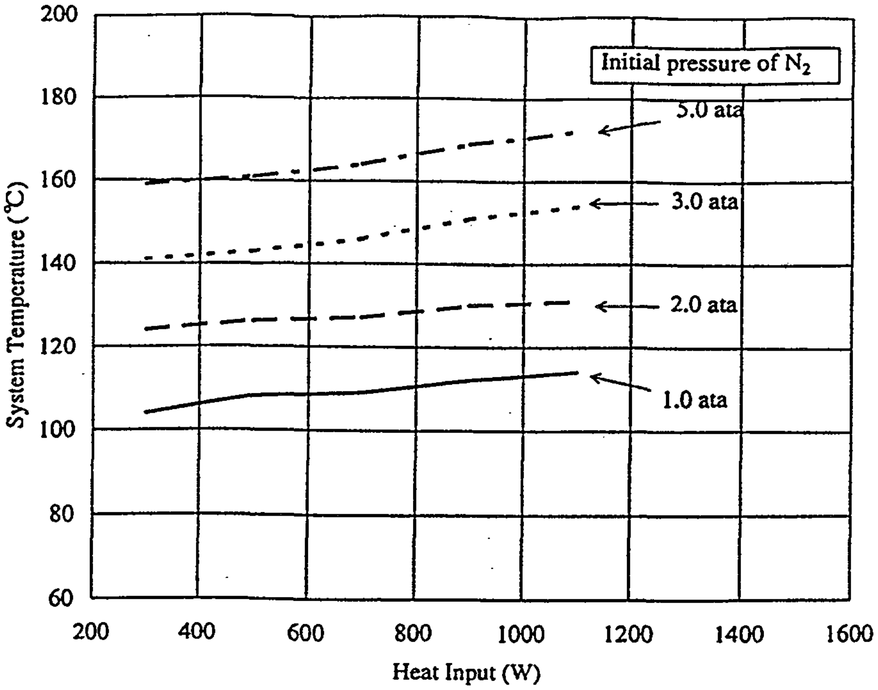

Fig.8 System Temperature Behaviors in Response to the Parametric Changes of Heat Inı
-Working fluid : Methnol-

The self-control mechanism supposed for these heat pipe systems is shown in Fig.9. During operation there may be formed a boundary between the vapor region and non-condensible gas region. Vapor region expands with the increase of heat input and compresses the gas volume to widen the condensing area, suppressing the system temperature rise consequence.

Analysis

The analysis to predict the thermal conditions of the system was done with focusing on the volume of nitrogen gas enclosed in the system, by combining the equation of state about the conditions of the nitrogen gas before and during operation with the relation between the heat input and the heat transfer and the relation between the saturated temperature and the pressure of the working fluid such as water or methanol.

With the nitrogen gas enclosed in the system, the thermal conditions can be expressed by equation of state before and during the system operation as follows;

$$\frac{PoVo}{To}=\frac{(Pv-Pvi)\{Vc(1-x)+Vr\}}{T2'} \quad (1)$$

In equation (1), Po, Vo, and To is the pressure, volume and temperature of the nitrogen gas before operation , and Vc and Vr are the volume of the condenser and the volume of the rest, i.e., the volume of the gas space below the condenser to the water surface in the return tube. Similarly, Pv and Pvi are the saturated pressure of the steam and the partial vapor pressure in the nitrogen gas respectively, and T2' is the temperature of the gas and x is the volumetric ratio of the condensing part in the condenser tube, all during operation. The saturated pressure Pv (ata) for the steam and methanol used in our analysis is shown in Table 1.

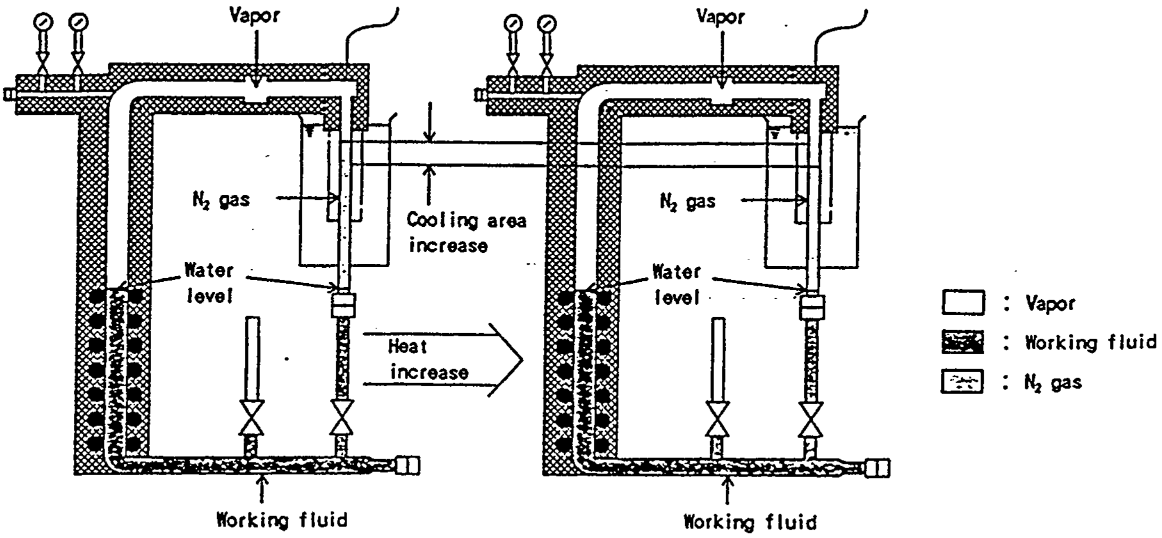

Fig.9 The self-control mechanism supposed in the separated type heat

Table 1. Saturated pressure Pv(ata) for steam and methanol

Working Fluid	Equation of saturated pressure	Note
Steam	$P_v=0.00031(T_v+273)^2-0.200(T_v+273)+32$ (Tv:50~100℃) $P_v=0.00129(T_v+273)^2-0.200(T_v+273)+32$ (Tv:100~200℃)	
Methanol	$\log P_v=8.07-\dfrac{1575}{T_v+238.9}$	Ref. 7

Tv; Saturated temperature (℃)

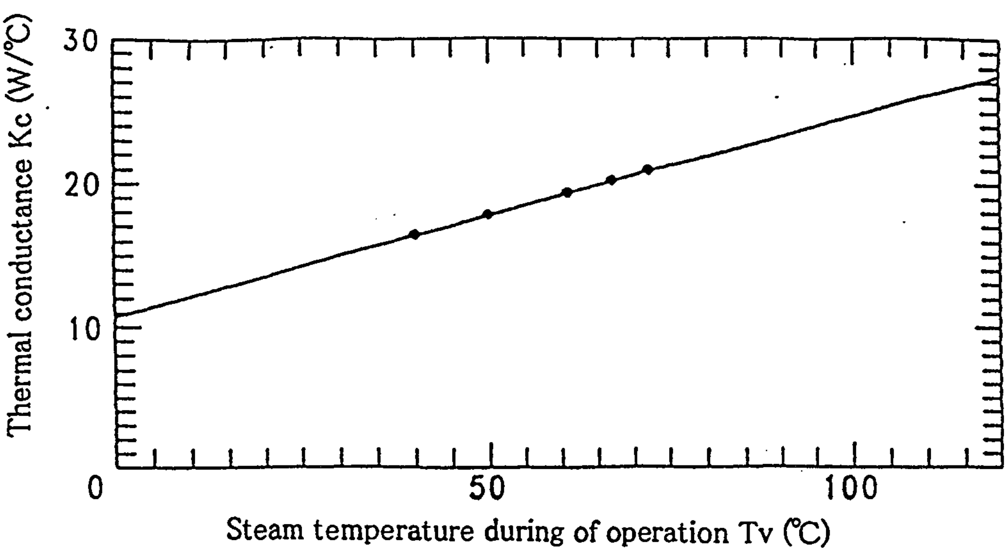

Fig.10 Thermal conductance Kc of the condenser v.s system temperature

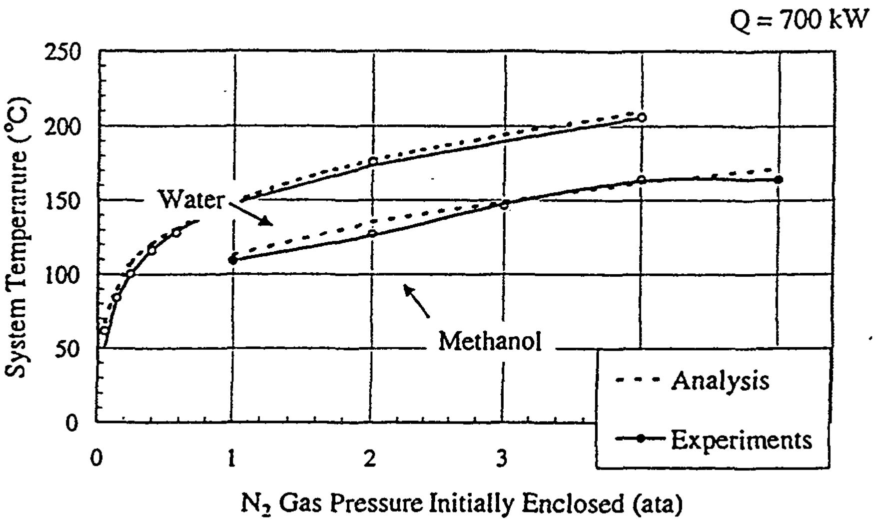

Fig.11 Comparison of the analysis with the experiments

The relation between the heat input Q and the heat discharging at the condensing part of the condenser is expressed as following;

$$Q = Kc \cdot x(Tv - Ts), \qquad (2)$$

where Kc is the thermal conductance of the condenser and Ts is the temperature of the heat sink. The values of the Kc used were derived from the data obtained from the experiments in the case of both water and methanol. For example, the thermal conductance Kc for water as working fluid is derived from the Fig.10.

Fig.11 shows the comparison of the system temperature to the nitrogen gas pressures enclosed on both the water and methanol as the working fluids calculated at the heat input Q=700W. The analytical results are fairly in good agreement with the experiments.

CONCLUSION

The Heat Pipe DHR system, which is fully passive up to the final heat sink, has a sufficient capability to maintain the reactor vessel temperature under its safety limit during accidents. Especially, by adoption of the variable conductance heat pipe, it is possible to design a fully passive DHR system, which can minimize the heat loss during normal operation and can achieve a lower reactor vessel temperature during accidents.

The experiments to obtain the fundamental characteristics data of the variable conductance heat pipe were carried out for the parametric changes of the heat input under the various pressures of non-condensing gas initially enclosed, including the experiments without enclosing the gas for comparison. Water and methanol were used as the working fluids and nitrogen gas was used as the non-condensible gas.

The experimental results showed very clear variable conductance features, i.e., self control characteristics. The working temperature of the system was clearly dependent on the pressure of the non-condensible gas initially enclosed, with higher system temperature with higher gas pressure enclosed. The mechanism of such features of the self control was made clear.

The analyses were done on water and methanol as the working fluids, which show very good agreement with the experimental results.

REFERENCES

1) R.P.Hills, "Air Natural Circulation Decay Heat Removal for small Gas-Cooled Reactors", DOE Sponsored Contract No.GCRA/REC/81-202
2) Nakanishi, S.Shimizu, Heat Pipe and Its Application, Ohm Ltd. (1984)
3) K.Ohashi et al, "Evaluation on Various Passive Decay Heat Removal System of Modular HTR", ANP '92, Oct.25 29,1992
4) S.S.Clark and J.F.Petersen, "TAC2D A General Purpose Two-Dimensional Heat Transfer Computer Code. Mathematical Formulations and Programmer's Guide", GA-9262, 1969.
5) Hayashi, et al, "Studies on the Characteristics of the Separated Thermo-Siphon System with Non-condensible Gas for the Use of the Passive Decay Heat Removal in Reactor Systems", The 3rd JSME/ASME Joint International Conference on Nuclear Engineering (ICONE-3), Proc.ICONE-3, Vol.2, 1143-1150 (1995)
6) T. Hayashi, et al, "Studies on the Characteristics of the Separated Heat Pipe System with Non-Condensible gas for the Use of the Passive Decay Heat Removal in the Reactor Systems," Eighth International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (Nureth-8), Kyoto, September 30-October 4,1997.
7) Hata, et al., Chemical Handbook, Rev.4, Maruzen Ltd.,(1993)