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차세대 신형원자로의 피동형 안전 주입장치를 위한 프리피스톤 스터링 펌프의 동특성 모델

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Dynamic Modeling of the Free Piston Stirling Pump for the Passive Safety Injection of the Next Generation Nuclear Power Plant

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Abstract

This paper describes a passive safety injection system with free piston Stirling pump working withabundant decay heat in the nuclear reactor during the hypothetical accident. The water column in the tube assembly connected from the hot chamber to the cold chamber in the pump oscillates periodically due to thermal volume changes of non-condensable gas in each chamber. The oscillating pressure in the water column is converted into the pumping power with a suction-and-bleed type valve assembly. In this paper a dynamic model describing the frequency of oscillation and pumping pressure is developed. It was found that the pumping pressure is a function of the temperature difference between the chambers. Also, the frequency of oscillation depends on the length of the tube with water column.

Key words: Stirling cycle, Oscillation, regenerator, resonacne, damping

1. Introduction

According to the passive safety concept introduced in the nuclear industry the active safety component such as the motor driven pumps are replaced by the gravity injection cooling water tanks. The core makeup Tank(CMT) and IRWST have been studied to supply safety cooling water into the reactor vessel directly following the gravity force. Sophisticated design activity has been performed for the optimum position and size of tubes related to meet the requested injection water flow rate during the hypothetical loss of coolant accident. The layout of the passive safety injection system is presented in Fig.1 where CP-1300 designed by the research group in CARR(Center for Advanced Reactor Research).

Besides gravity injection, there may be many alternatives for the passive safety injection . As one of alternatives, the free piston Stirling pump is proposed here to hybrid the merits of pump and passive character of stirling system. The electric powered pump categorized as an active component could not in service without electric power supply. In such an accidental situation if we could provide a pump powered by thermal energy in the nuclear reactor, it could be recognized as the passive safety components like gravity injection system. The heat transfer from hot area to the cold is as natural as gravitational moving from high position to the low position.

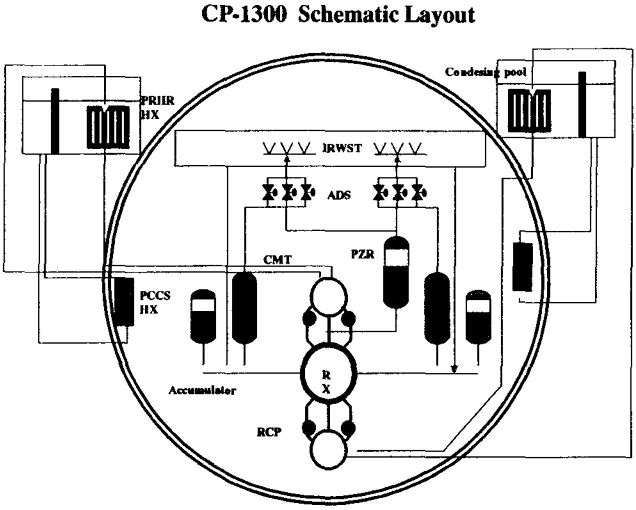
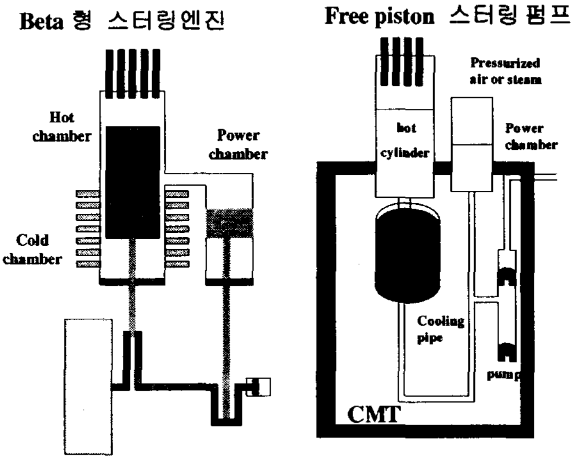


Fig.1 The schematic layout of the passive safety system of CP1300

II. Stirling pump and its operating principle

As shown in the left figure in Fig. 2, the present free piston stirling pump has two chambers of hot and cold states. They are connected by a long tube filled with water. This long tube has a branch to provide pressure oscillation to the pumping valves assembly where two check valves and orifices.


Beta 형 스터링엔진

Free piston 스터링 펌프

Fig.2 The conceptual drawing of the Stirling engine and Stirling pump.

As shown in Fig.3, if the negative pressure is imposed to the valve system, while the upper valve is closed, the bottom valve is opening up so that water flow into the pump cylinder. But the positive pressure resulting from the oscillation of the water column in the long tube expels out the water inside the pump chamber through the opened upper valve. This simple but positive pumping action will be continued as long as the oscillation of the water column is proceeding. The present free piston stirling pump is similar to the beta type stirling engine. The piston and flywheel and crank assembly are replaced by the long U-tube. there is no mechanical moving parts in the inside of the free stirling pump. Therefore, it has the same merits as the Stirling engine such as the auto startup.

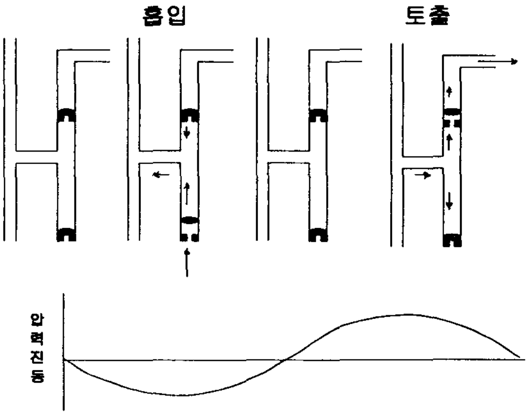


Fig.3 The operating procedure of valve assembly to pump up water

III. Modelling of the Stirling Pump

Since the stirling engine has not been in the leading position in the engine industry, the modelling of the stirling engine is still in the primitive stage. The Shumidt theory has been widely accepted and used for the design of the Stirling Engine. At least the thermal design and determination of the power output, it could produce reliable results. The major drawback of this theory is the assumption of the crank motion in forms of periodic sine function[2,3,4]. However, for the present stirling pump[5], it is not a good assumption that the water column oscillation in sine function. To get realistic understanding and design basis, the dynamic oscillation of the water column should be modelled. It could be addressed by using the force balance acting to the water column and the equation of state for the non-condensable gas in the chamber.

Let the water level be at x, the force acting on the water column could be described by adding all related forces such as the gravitational head, pressure difference between the chambers and the friction generated by the water column flow.:

$$F = M_{water}\frac{d^2x}{dt^2} = 2\rho gx + (P_H - P_C)A_c + k\frac{L}{A_t}\frac{dx}{dt} \tag{1}$$

where M_{water} means the mass of the water column, x the position of the water level in the hot chamber measured from the middle of the chamber. The ideal gas law is applied to convert pressure to the water level position :

$$P_H V_h = mRT_H \tag{2}$$

The pressure in the hot chamber is

$$P_H = \frac{mRT_H}{A_c(H_0 - x)} \tag{3}$$

Also, the pressure in the cold chamber could be formulated as :

$$P_C = \frac{mRT_C}{A_c(H_0 + x)} \tag{4}$$

For simplicity, the cross sectional area of both chambers are assumed as the same. Let us make the pressure difference between chambers which will acts as a driving force of the water column.

$$P_H - P_C = \frac{mR}{A_c}\left(\frac{T_h}{H_0 - x} - \frac{T_c}{H_0 + x}\right) \tag{5}$$

The pressure force resulted has the non-linearity with respect to water level position, x.:

$$(P_H - P_C)A_c = \frac{mRT}{H_0^2}\left(\frac{\Delta T + 2T_{avg}\left(\frac{x}{H_0}\right)}{1 - \left(\frac{x}{H_0}\right)^2}\right) \tag{6}$$

the non-linearity effect increasing as the chamber diameter is decreasing which produces a big displacement of the water level. In this paper, the requirement of the periodic oscillation for the reliable operation of pump limit the diameter of the chamber to the extent that nonlinear terms could be destroyed fast. This means that $\frac{x}{H_0}$ is small enough to be neglected from the second power of it. Let us denote it as ε and expand the above relation in series ($\varepsilon = \frac{x}{H_0}$)

$$(P_H - P_C)A_c = mR\Delta\frac{T}{H_0}\left(1 + 2\frac{T_{avg}}{\Delta T}\varepsilon\right)(1 + \varepsilon^2 + \varepsilon^4 + \cdot\cdot\cdot) \tag{7}$$

After removing the higher order terms than the first order, the following linear pressure force term is derived:

$$(P_H - P_C)A_c = mR\Delta\frac{T}{H_0}\left(1 + 2\frac{T_{avg}}{\Delta T}\frac{x}{H_0}\right) \tag{8}$$

Inserting Eq.(8) into the force balance equation, Eq.(1) yields the following dynamic equation for the water column oscillation:

$$M_{water}\frac{dx^2}{dt^2}=\frac{MR\Delta T}{H_0}+2\left(\rho g+\frac{mRT_{avg}}{H_0^2}\right)x+K\frac{L}{A_t}\frac{dx}{dt} \tag{9}$$

The first term in the right hand side is the force source which is proportional to the temperature difference between chambers. The pressure source will be dissipated as the pumping force to inject cooling water to the nuclear reactor vessel. The second term in R.H.S is correspondent to the spring force generating oscillation of water level. And the last term is the frictional force action as the damper of the oscillation amplitude. The above equation is well understood as the spring damper system.

IV. Results and Discussions

The oscillation period is proportional to the stirling pump cycle. When revolution speed is resonant with the system oscillation period stirling engine, the maximum stirling power is expected. The drawback of the Schumidt theory, used as a design method for a long time, is its assumption of the revolution speed. From Eq.(9), the period of oscillation of the water column is derived as :

$$T=\frac{2\pi}{\sqrt{\frac{2\left(\rho g+\frac{mRT_{avg}}{H_0^2}\right)}{M_{water}}}} \tag{10}$$

This oscillation is damped in the exponential way with the parameter:

$$e^{-\frac{KLt}{A_t M_{water}}} \tag{11}$$

The stable fixed point is determined by the external force

$$x=\frac{MR\Delta T}{2H_0\left(\rho g+\frac{mRT_{avg}}{H_0^2}\right)}$$

This potential energy is converted as the pumping force in accordance with the Pascal law:

$$\Delta p=\rho g x\frac{A_{hot}}{A_{pump}} \tag{12}$$

Since the core makeup tank of the next generation reactor is connected directly to the reactor vessel, if the pumping pressure could overcome the friction loss and the system pressure oscillation due to the mismatch between the inflow from the CMT and blowdown flow.

V. Conclusions

The present model provides a dynamic model for the free piston Stirling pump to be used as an alternative passive safety injection system of the next generation nuclear reactor. Its dynamics is similar to the spring damper system with a constant external force. The temperature difference between the hot and cold chamber is a key parameter to determine pumping pressure. Further studies are remained to determine the optimum way of decay heat supplying to the hot chamber. Also, the volume reduction by enhancing its efficiency should be considered further.

Acknowledgement

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