Analysis on thermophoretic deposit of fine particle on water wall of 10 MW high temperature gas-cooled reactor

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Abstract The water wall is an important part of the passive natural circulation residual heat removal system in a high temperature gas-cooled reactor. The maximum temperatures of the pressure shell and the water wall are calculated using annular vertical closed cavity model. Fine particles can deposit on the water wall due to the thermophoresis effect. This deposit can affect heat transfer. The thermophoretic deposit efficiency is calculated by using Batch and Shen's formula fitted for both laminar flow and turbulent flow. The calculated results indicate that natural convection is turbulent in the closed cavity. The transient thermophoretic deposit efficiency rises with the increase of the pressure shell's temperature. Its maximum value is 14%.

Keywords High temperature gas-cooled reactor, Water wall, Fine particles, Thermophoretic deposit
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1 Introduction

Energy resources problem is an urgent and important project in the world today, and development of the high temperature gas-cooled reactor is a strategic arrangement in China. In 2002, the first 10 MW high temperature gas-cooled reactor was built in Tsinghua University. There is a peculiar advantage of thermoelectricity joint production with the high temperature gas-cooled reactor. Since it can provide heat to high temperature technology besides electric power generation, the high temperature gas-cooled reactor will occupy a specially important place[1] in Chinese energy resources in the future. So far the high temperature gas-cooled reactors are designed with passive safety characteristics, which do not depend on the external conditions, but on such natural regulations for enhancing safe function as gravity-rule (potential difference) and the thermal transmission rule (natural convection).[2] The water wall is heat transfer connecting link between the preceding and the following parts of the passive natural circulation residual heat removal system. To study its heat transfer is important. Because of temperature difference between the water wall and the pressure shell, fine particles can move to wall-cooling surface due to the action of temperature gradient. The thermophoretic deposit of fine particles can affect the heat conductivity of the water wall and the heat transfer mechanism. To ensure safe and economic operation for the high temperature gas-cooled reactor, we consider it very essential to study thermophoretic deposit of fine particles on the water wall and to know the details of heat transfer and residual heat.

2 Operating principle

2.1 Structure and location

The water wall[3] is a main heat transfer equipment of the passive natural circulation residual heat removal system in the high temperature gas-cooled reactor. The system is illustrated in Fig.1.

The water wall of the passive natural circulation residual heat removal system is located inside screen concrete wall of the reactor cabin. It is a cylinder wall

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around the reactor, as shown in Fig.2. The plate is made of jointing steel plate and seamless steel tube. Two groups of water cooling tube bundles are arranged uniformly on the water wall along with circumference. They are arranged with the interval mode each other, and there are two fixed supports and four glided supports per plate, which is suspended on embedded parts built in screen concrete. The support abutment of the pressure shell gets through the water wall. The cooled water in the support abutment is connected with water tube of the water wall. There are gates of channel of helium canal on the water wall. Then, the upper and lower water tube of two systems are joined to the independent water wall header separately. The upper and lower water wall headers are made of closed annular tube and their tubes are connected to inlet and outlet of the air radiator with pipeline separately.

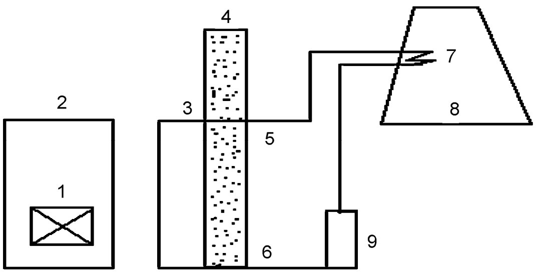

Fig.1 Sketch of the 10 MW passive natural circulation residual heat removal system of the high temperature gas-cooled reactor.
1. Reactor core, 2. Pressure shell, 3. Water wall, 4. Concrete wall of reactor cavity, 5. Inlet duct, 6. Outlet duct, 7. Air radiator, 8. Chimney, 9. Water tank.

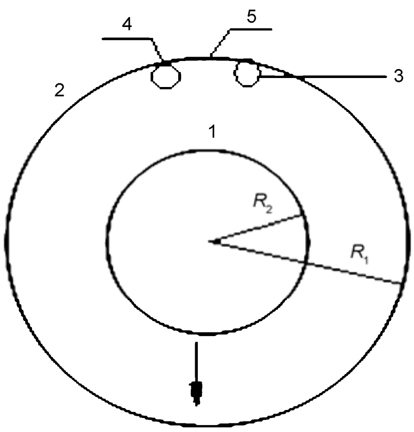

Fig.2 Planform of the pressure shell and water wall of the high temperature gas-cooled reactor.
1. Pressure shell, 2. Water wall, 3. One group of water cooling tubes, 4.Other group water cooling tube, 5. Steel plate.

2.2 Heat transfer and thermophoretic deposit

In 10 MW high temperature gas-cooled reactor, when loss of pressure accident occurs on coolant (nitrogen) of one loop, and in the meantime the main heat transfer system happens on invalidation, residual heat will be not able to discharge from the main heat transfer system. Instead, residual heat can be discharged by using graphite reflector and the pressure shell through heat exchange and heat radiation. At last, it is transferred to the water wall located around the pressure shell through two kinds of modes (radialization and natural convection). The water cooling tubes of water wall are connected to air radiator located in upper space of the chimney and form natural circulation loop. There are not motile parts in this system. The system relies on natural circulation and transfers heat to air side for carrying residual heat out. There are two group water cooling tubes separately, and every group has residual heat removal capacity. Power per residual heat removal system is designed to be 134 kW.

Under accident situation, because there are big temperature gradient between the water wall and the pressure shell, fine particles can move to the wall-cooling surface and deposit on wall-cooling surface. This is named the thermophoretic deposit process. Obviously, heat conductivity of water wall is variable due to the thermophoretic deposit, then, there are some effects on heat transfer or temperature change of the residual heat removal system.

3 Calculation models

3.1 Radiation heat exchange model

Radiation heat exchange is a main mechanism when the pressure shell of a high temperature gas-cooled reactor transfers heat to the water wall. Angle coefficient is crucial if radiation heat exchange must be calculated exactly. There are many calculation methods about angle coefficient and radiation heat exchange.[4-7] Diagram method[4] and Hottel method[6] are selected to calculate angle coefficient and radiation heat exchange respectively. According to structure mode of the cavity between the pressure shell and the water wall, interlayer air is known as heat transparent body, and radiation heat exchange is known as heat transfer analysis between two finite length concentric grey body cylinders.

A formula of calculating angle coefficient between two finite length concentric cylinders is obtained for the geometry shown in Fig.3.[6]

Assume

$X=b/a$, $Y=c/a$,

$A=Y^2+X^2-1$, $B=Y^2-X^2+1$,

then

$$\phi_{11}=1-\frac{1}{X}+\frac{2}{\pi X}\arctan\left[\frac{2(X^2-1)^{1/2}}{Y}\right]-\frac{Y}{2\pi X}\times$$
$$\left\{\frac{(4X^2+Y^2)^{1/2}}{Y}\times\arcsin\left[\frac{4(X^2-1)+\frac{Y^2}{X^2}(X^2-2)}{Y^2+4(X^2-1)}\right]-\right.$$
$$\left.\arcsin\frac{(X^2-2)}{X^2}+\frac{\pi}{2}\left[\frac{(4X^2+Y^2)^{1/2}}{Y}-1\right]\right\} \quad (1)$$

$$\phi_{12}=\frac{1}{X}-\frac{1}{\pi X}\left\{\arccos\frac{B}{A}-\frac{1}{Y}\left\{\left[(A+2)^2-4X^2\right]^{1/2}\times\right.\right.$$
$$\left.\left.\arccos\frac{B}{XA}+B\arcsin\frac{1}{X}-\frac{\pi A}{2}\right\}\right\} \quad (2)$$

$$\phi_{13}=\frac{1}{2}(1-\phi_{12}-\phi_{11}) \quad (3)$$

$$\phi_{21}=1.0 \quad (4)$$

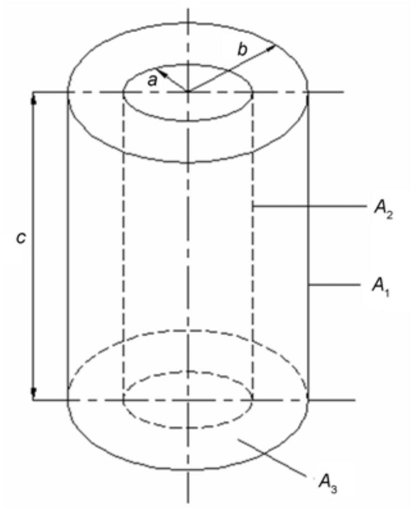

Fig.3 Sketch map on angle coefficient calculation of two cylinders.

The outer wall of the pressure shell and the water wall are considered as a grey cavity consisting of surfaces of two finite length concentric cylinders. Third closed cover is an isothermal black body from Hottel[6]definition, then:

$$Q_{21}=\frac{\varepsilon_1\varepsilon_2A_2\phi_{21}C_s}{1-(1-\varepsilon_1)(1-\varepsilon_2)\phi_{21}\phi_{12}}\times$$
$$\left[\left(\frac{T_2}{100}\right)^4-\left(\frac{T_1}{100}\right)^4\right] \quad (5)$$

where Q_{21} is radiation heat from the surface of the pressure shell to the surface of the water wall (kW); ε_1 is emissivity of the water wall surface; ε_2 is emissivity of the pressure shell surface; ϕ is angle coefficient; A is surface area (m^2); C_s is radiation coefficient of black body, 5.67 W•m^{-1}•K^{-4}; subscript 1 refers to the surface of the water wall; 2 to the surface of the pressure shell.

3.2 Natural convection heat transfer

Natural convection is another important mode of heat transfer from the outer surface of the pressure shell to the surface of the water wall. The cavity between the pressure shell and the water wall is an annular perpendicular interlayer. Due to the big ratio of height to width (h/δ), the heat exchage can be considered as natural convection in a closed perpendicular rectangle cavity. Now, there are many empirical formulae. We have chosen the formulae on the closed perpendicular rectangle cavity suggested by MacGregor and Emery:[8]

$$Nu_\delta=0.42Ra_\delta^{1/4}Pr^{0.012}(h/\delta)^{-0.3} \quad (6)$$

for $10<(h/\delta)<40$; $1<Pr<2\times10^4$; $10^4<Ra_\delta<10^7$, and

$$Nu_\delta=0.046Ra_\delta^{1/3} \quad (7)$$

for $10<(h/\delta)<40$; $1<Pr<20$; $10^6<Ra_\delta<10^9$,

where δ is width between two heat transfer surfaces (m); h is height of rectangle (m); Rayleigh number $Ra=[g\beta(T_i-T_o)\delta^3]/(av)$, where T_i, T_o is wall temperature (K) of the pressure shell and the water wall respectively; β is expansion coefficient of gas cubage (K^{-1}); a is molecule's thermal diffusivity (m^2•s^{-1}); v is kinematic viscosity coefficient (m^2•s^{-1}); and g is acceleration of gravity (m•s^{-2}).

3.3 Heat conduction equation of water wall tube

Heat transfer in the plate rib and the water tube wall of the water wall is usually equivalent to one tube for calculation. The heat conduction equation can be expressed by[9]

$$\rho C_p \frac{\partial T(r,t)}{\partial t} = \frac{1}{r} \times \frac{\partial}{\partial r}\left(\lambda r \times \frac{\partial T(r,t)}{\partial r}\right) + q_v(r,t) \quad (8)$$

where ρ is density of material (kg•m^{-3}); C_p is specific heat of material (kJ•kg^{-1}•s^{-1}); λ is heat conduction coefficient of material (kW•m^{-2}•K^{-1}); q_v is heat generated rate per unit volume (kW•m^{-3}).

Due to thin water tube wall, lumped parameter is adopted, and axis and circumferential heat conduction are neglected, then the heat conduction equation of tube wall becomes:

$$M_w C_{Pw} \frac{\partial T_{o,w}(t)}{\partial t} = \alpha_1 F_{i,w}\left(T_{f,1} - T_{i,w}\right) - \alpha_2 F_{o,w}\left(T_{o,w} - T_{f,2}\right) \quad (9)$$

$$\frac{\partial T_{i,w}(t)}{\partial t} = \frac{\partial T_{o,w}(t)}{\partial t} \quad (10)$$

with the boundary conditions: a certain steady heat transfer coefficient H_∞ and heat sink temperature T_∞; where M_w is tube wall mass per unit length (kg); C_{Pw} is specific heat of tube wall (kJ•kg^{-1}•K^{-1}); α_1 is coefficient of heat transfer between tube wall and fluid inside the tube (kW•m^{-2}•K^{-1}); $F_{i.w}$ is surface area of heat transfer in the tube (m^2); α_2 is coefficient of heat transfer between tube wall and liquid outside the tube (kW•m^{-2}•K^{-1}); $F_{o.w}$ is surface area of heat transfer out side the tube (m^2); $T_{f,1}$, $T_{f,3}$ is fluid temperature inside the tube and outside the tube respectively (K); $T_{i,w,}$ $T_{o,w}$ is temperature of inner and outer tube wall respectively (K).

3.4 Heat conduction equation of plate rib of water wall

One water tube of the water wall is connected to other water tube with a plate rib, and the plate rib is shown in Fig.4.

Due to thin thickness of the plate rib, heat conduction of the thickness direction (z) can be neglected, then a two dimension transient heat conduction equation is obtained:

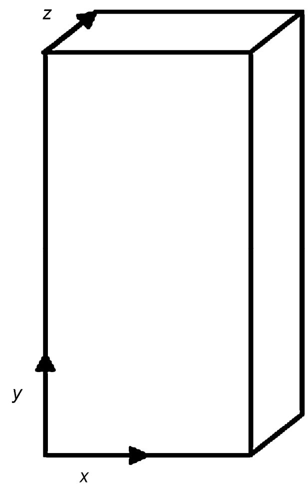

Fig.4 A plate rib.

$$\rho c \frac{\partial t}{\partial \tau} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) z + q \quad (11)$$

where λ is heat conduction coefficient (kW•m^{-1}•K^{-1}); T is temperature (K); z is thickness of plate rib (m); q is heat flux density of radiation and natural convection (kW•m^{-2}).

There are three boundary conditions:

1. When Y direction (height) of control body is far bigger than X direction (width) of control body, the upper and lower boundary of the plate rib are considered as thermal insulation.

2. When two water tubes of the same kind are put into operation in the meantime, symmetric temperature field is produced on the plate rib between two tubes. If its symmetric axis is considered as boundary, boundary condition of the plate rib is considered as thermal insulation.

3. When one water tube is put into operation, since two water tubes are arranged through interval mode each other and water does not flow in one side tube, one boundary of the plate rib is considered as thermal insulation.

Therefore, boundary conditions of the equation are thermal insulation on three sides (one X side; two Y sides) and heat conduction on one side (one X side).

3.5 Convection heat transfer in water tube

Newton cooling law can be used to calculate absorbing heat of the water wall's surface and carrying heat of fluid in tube, i.e:

$$Q = hA\Delta t \quad (12)$$

where Q is heat the solid wall transfers to fluid (kW); A is surface area of heat transfer (m^2); Δt is temperature difference (K); h is convection transfer heat coefficient ($kW \cdot m^{-2} \cdot K^{-1}$). Transfer heat coefficient is dependent on flow situation. There are many alternative calculation formulae in references.[6,7,10]

3.6 Thermophoretic deposit efficiency

Under accident condition, because there is temperature difference between the pressure shell and the water wall, fine particles can be sent from the high temperature surface to the low temperature surface, and this process is called thermophoresis effect. Thermophoresis coefficient K_{th} is a symbol of this characteristic, and can be calculated using the following formula[11]

$$K_{th} = \frac{2C_s C}{(1+3C_m Kn)} \times \frac{[\kappa^{-1} + C_t Kn]}{[1+2\kappa^{-1}+2C_t Kn]} \quad (13)$$

where κ is ratio of heat conduction, i.e. $\kappa = \kappa_p / \kappa_g$, κ_p and κ_g is heat conductivity of fine particles and gas respectively; C_m=1.146; C_s=1.147; C_t=2.20; C=1.0+$Kn[C_1+C_2\exp(-C_3/Kn)]$, where C_1=1.2; C_2=0.41; C_3=0.88; Kn is Knudsen number.

In 1985, Batchelor and Shen[12] proposed a formula on thermophoretic deposit efficiency fitted for both laminar flow and turbulent flow:

$$\eta = \frac{PrK_{th}}{T_w}(T_e - T_w)\left[1 + (1 - PrK_{th})\left(\frac{T_e - T_w}{T_e}\right)\right] \quad (14)$$

where T_e and T_w is inlet fluid temperature and tube wall temperature respectively (K); Pr is gas Prandtl number.

4 Calculation and analysis

There are some assumptions before calculation. At first, all of received heat radiation and natural convection for the plate rib are given to water tube, and radiation of the plate rib to screen concrete wall is neglected. Secondly, due to thin thickness of the plate rib, heat conduction of thickness direction (z) is neglected. Finally, circumferential and radial temperatures are uniform, and non-uniformity of temperature field of tube wall is neglected. Power of radiation and natural convection is taken as the input boundary under the given accident situation. Transient temperatures of the pressure shell and the water wall in the high temperature gas-cooled reactor are calculated using the above mentioned method from Section 3.1 to Section 3.5. At last, transient thermophoretic deposit efficiency of the water wall is calculated using the method described in Section 3.6. Temperature distributions of the pressure shell and the water wall in the high temperature gas-cooled reactor are not uniform, so thermophoretic deposit efficiency is not uniform too. To simplify the calculation, the maximum transient temperature is adopted.

Input power (PW1) and the power carried by the water wall (PW2) are shown in Fig.5.

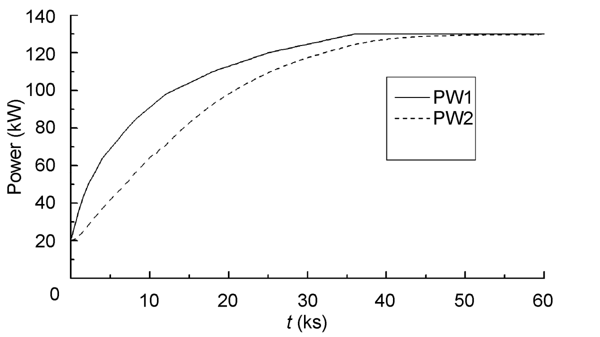

Fig.5 Transient change of power.
PW1: Radiation and natural convection power (input boundary); PW2: Power carried by the water wall.

From Fig.5, we have found that the power carried by the water wall increases with input power's increasing. PW2 is smaller than PW1 in the first 50 ks, but both are almost equal with development of the accident (after 50 ks).

The maximum transient temperature of the pressure shell is shown in Fig.6 when input power is PW1.

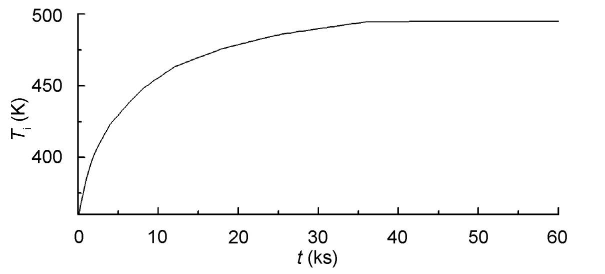

Fig.6 Maximum transient temperature of outer wall of the pressure shell using the radiation model (given PW1).

From Fig.6, we can see that the input power and power carried by the water wall get to balance after 35ks. The maximum temperature of the outer wall of pressure shell gets to a steady value (490 K or so).

The maximum transient temperature of the water wall is shown in Fig.7.

From Fig.7, we can see that the maximum transient temperature of the water wall keeps almost at 336 K because fluid in water tube has a strong heat transfer capability.

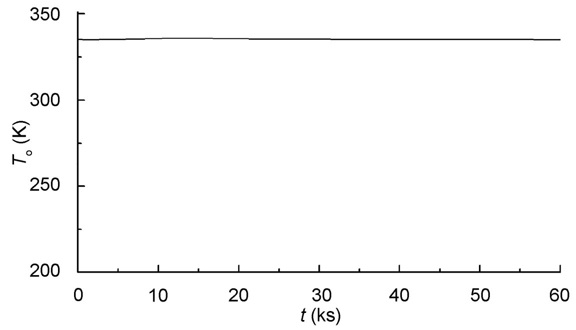

Fig.7 Maximum transient temperature of the water wall.

Thermophoretic deposit efficiency of PM2.5 is calculated based on the temperature difference between the outer wall of pressure shell and the water wall. R_1=2.95 m is outer radius of annular cavity consisting of the pressure shell and the water wall; R_2=2.18 m is outer radius of the pressure shell; H=9.5 m is height of annular cavity; δ=0.77 m is distance between the outer wall of pressure shell and the water wall.

According to Rayleigh in formulae (6) and (7) $Ra=[g\beta(T_i-T_o)\delta^3]/(av)$, then:

when $t \leqslant 0.3$ ks, $T_i \leqslant 400$ K, $Ra \leqslant 1.01\times10^9$ (laminar flow);

when $t \geqslant 0.3$ ks, $T_i \geqslant 400$ K, $Ra \geqslant 1.01\times10^9$ (turbulent flow);

when T_i=490 K, $Ra=1.49\times10^9$ (turbulent flow).

Obviously, when $t \leqslant 0.3$ ks, due to few temperature difference between the outer wall of pressure shell and the water wall, thermophoretic deposit efficiency of PM2.5 is small. So, this condition need not be calculated here. The thermophoretic deposit efficiency on turbulent flow is shown in Fig.8 when $t \geqslant 0.3$ ks. The result is calculated using formula (14).

From Fig.6 and Fig.8, we can see that temperature of the pressure shell increases continuously with time, and leads to enhancement of the thermophoretic deposit efficiency, and the maximum thermophoretic deposit efficiency can get to 14%. If TSP concentration of 0.5 mg•m^{-3} is adopted in air, and the cavity composed of the pressure shell and the water wall is considered as a closed space, then, there is ash in the cavity:

$$W=0.5\times H\times\pi(R_1^2-R_2^2)=0.5\times9.5\times(2.95^2-2.18^2)$$
$$=18.763 \text{ mg};$$

then thermophoretic deposit is

$$W_1=\eta\times W=0.14\times18.763=2.627 \text{ mg};$$

thermophoretic deposit per unit area is

$$GS=W_1/(H\times2\pi R_1)=2.627/(9.5\times2\pi\times2.95)$$
$$=0.01493 \text{ mg/m}^2.$$

Therefore, quantity of fine particles in thermophoretic deposit on the surface of the water wall is small and can not form big absolute amount of ash. But total deposit efficiency can be bigger than the value calculated as above when a turbulent flow is considered. Obviously, if there are high fine particle concentrations in the closed cavity, thermophoretic deposit efficiency of 14% is also very considerable.

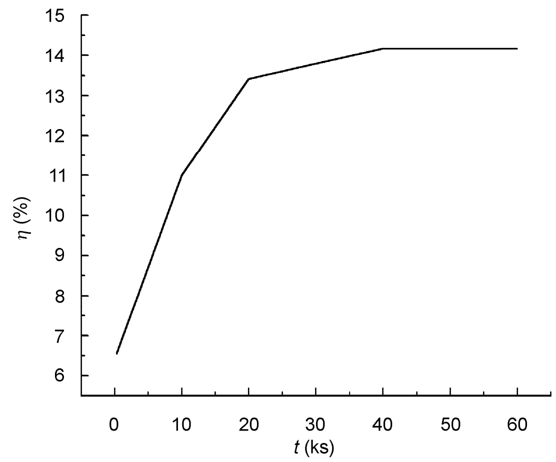

Fig.8 Thermophoretic deposit efficiency of the surface of the water wall.

5 Conclusion

1) Under general accident conditions, fine particles are sensitive to temperature gradient and absolute amount of fine particles in thermophoretic deposit is small. The fine particles have little effect on heat conductivity of the water wall. It almost has no effect on the whole passive natural circulation residual heat

removal system of the high temperature gas-cooled reactor. The thermophoretic deposit effect for the system can be neglected under certain conditions.

2) It is noticeable that the thermophoretic deposit efficiency of the water wall is big. If there are more fine particles in the cavity when many fine particles are leaked from the pressure shell and air is not clear in the cavity in the extreme situation, the thermophoretic deposit and other deposit can cause heat conductivity of the water wall to change so that the safe parameters of whole passive natural circulation residual heat removal system of the high temperature gas-cooled reactor are changeable. So we must pay attention to cleanliness of air in the cavity.

3) The statement in this paper only depends on the calculated result of the maximum temperature between the outer wall of the pressure shell and the water wall. The temperature difference between the outer wall of the pressure shell and the water wall increases and tends to a steady value with time increasing, so the thermophoretic deposit efficiency increases to steady value. When the maximum temperature difference appears, it have to be noticed that the change of heat transfer has an effect on the safe mechanism of the system. In fact, transient temperature along with the height of the cavity can be calculated easily, so the thermophoretic deposit efficiency can also be calculated easily between any temperature difference between the outer wall of the pressure shell and the water wall. Nevertheless, the thermophoretic deposit efficiency formula is not very mature today. These calculations will have to be verified in experiments in the future. More research work must be done. But basic rules suggested in this paper are right, important and useful.

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