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THEORETIC ANALYSIS FOR GRAVITY SEPARATION OF WATER DROPLETS IN PWR STEAM GENERATOR

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压水堆蒸汽发生器水滴重力分离的理论研究

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摘　要

压水堆蒸汽发生器水滴重力分离空间是汽水分离装置的重要组成部分，是连接汽水分离器和蒸汽干燥器的纽带。蒸汽发生器的设计，除了要选用分离效率高，结构紧凑的汽水分离器和干燥器外，还要合理选择重力分离空间高度。高度太低，湿分得不到充分的重力分离，将会影响干燥效果；高度太高，将会增加蒸汽发生器和核岛设施的投资。文中对重力分离空间蒸汽携带水滴的过程进行了理论研究，推导出了水滴重力分离高度，水滴的飞升直径和飞升速度的一般表达式，在分析中还考虑了汽液两相间速度的不一致（即滑动比S），并提出了直径-粘度组合项。理论研究得出的结论可为确定蒸汽发生器重力分离空间高度提供依据。

THEORETIC ANALYSIS FOR GRAVITY SEPARATION OF WATER DROPLETS IN PWR STEAM GENERATOR

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ABSTRACT

Gravity separation space of water droplets in the PWR steam generator is one of three important separating mechanisms and provides a link between primary (vane) separator and chevron dryer. The design of steam generator should not only have highly efficient and compact separator and dryer, but also an adequate height of gravity separation space. Too short a gravity separation space will not sufficiently separate the moisture and adversely affect the performance of the dryer; Too long a gravity separation space will add additional costs for steam generator and nuclear island installation. The droplet entrainment in the process of gravity separation space was theoretically studied and droplet trajectory was analytically modelled. A general expression for the height required by gravity separation, diameter and velocity of those droplets carried over was also obtained. In the analysis, the slip between two phases was considered and a combined term of diameter and viscosity was introduced. The modelling can provide a theoretical basis for determining the height of the gravity separation space.

INTRODUCTION

Steam-water mixture separation in a PWR natural circulation steam generator consists of primary (vane type) separator, chevron type dryer and a gravity separation space (see Fig. 1).

Steam-water mixture from the top of tube bundle is first separated by the primary separator. The water is in part entrained out of the primary separator and enters the gravity separation space. While larger droplets are separated by gravity, smaller ones are carried up further and enter the dryer where the moisture level of steam flow is further reduced to the required value of 0.25% or below.

PWR steam generator undertakes a very heavy loading and supplies very high quality steam. Not only must the primary separator and chevron dryer be correctly designed, but also an adequate height should be kept for gravity separation space.

If the adequate height can not be ensured, the dryer will be overloaded. On the other hand, an excessive height does not improve the separation efficiency but wastes the manufacture cost. In the past, domestic steam generator design took a similar height for gravity separation to the foreign counterparts, which was not well founded in theory. This paper investigates into the process of gravity separation in an attempt to improve the design of domestic steam generator.

Droplet entrainment is clearly described and droplet trajectory is analytically modelled in the gravity separation space. Momentum equations are used to obtain an explicit expression of the gravity separation height, from which the designer can determine the required gravity separation height and the size of droplets entering the dryer when the granulometry of droplets at the exit of the primary separator is known.

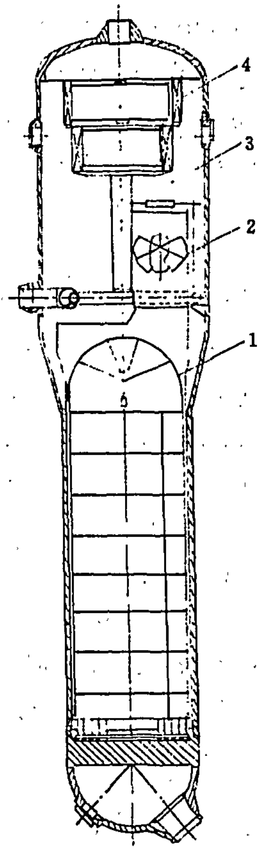

Fig. 1 Schematic of PWR steam generator

1——tube bundle;
2——primary separator;
3——gravity separation space;
4——chevron dryer.

1 ENTRAINMENT PROCESS OF DROPLETS

Not all the droplets ejected out of the primary separator can be carried over to enter the dryer. Some of larger diameter can only flow up to a certain height and then fall down. This height is called the droplet gravity separation height (GSH).

Those small droplets whose GSH exceeds the actual distance existing from the primary seperator will enter the dryer. The gravity separator height is related to the following factors:

(1) Droplet initial velocity.

(2) Droplet dragged by steam. There are two different cases: (i) when the droplet flows up faster than steam, the drag tends to consume the droplet kinetic energy. (ii) when the droplet flows up slower than steam, the drag tends to prevent it falling down, that is, droplet entrainment. For very small droplets, the entrainment can overcome their weight so that they could be carried up to any height, they are called Entrainable Droplets.

(3) Steam generator loading. Increase of loading can aggravate the entrainment process.

(4) Dome pressure. Operating pressure, if elevated, can reduce the density ratio of steam and water and increase the entrainment.

Because of the short transit time for droplets in the gravity separation space, the evaporization and condensation are both neglected.

2 DROPLET GRAVITY SEPARATION

2.1 Momentum equation

The following analysis is made on the basis of these assumptions:

(1) Droplets take shape of a ball,

(2) Droplet motion is governed by Stokes' Law,

(3) No evaporization and condensation,

(4) Droplet motion is of one dimension,

(5) Cross-section of the gravity separation space is constant along the height.

Fig. 2 shows a schematic of steam-water separator of PWR steam generator. The one dimensional axis is placed along the steam generator centerline.

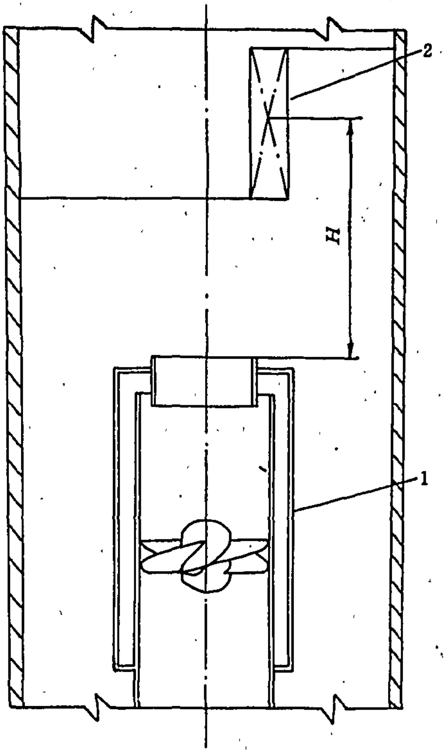

Fig. 2 Schematic of steam generator separator

1——primary separator

2——dryer

The steam-water two-phase flow comes out of the primary separator and then, the resultant steam and droplets enter the gravity separation space respectively at velocity of U_s and U_d. The droplets slow down by gravity, buoyancy and drag combined, until their velocity is equal to that of the steam at a height of H_1. Therefore, the droplets existing from the primary separator to H_1 move faster than the steam, that is $U_{dz}>U_s$.

Thereafter, because of inertia and drag, they will continue to move up till to a height of H_2 where they cease going up, that is, $U_{dz}=0$. Form H_1 to H_2, the droplets move slower than steam, that is $U_{dz}<U_s$.

2.1.1 Droplet velocity is greater than steam velocity when $U_{dz}>U_s$, the droplets are forced by:

(1) drag of steam flow

$$R_1=-\frac{\pi}{8}\zeta D_d^2\rho_s\left(\frac{dz}{dt}-U_s\right)^2 \tag{1}$$

where R_1——drag;
ζ——drag coefficient;
t——time;
D_d——droplet diameter.
z——axial coordinate;
ρ_s——steam density;
U_s——steam velocity;

(2) Buoyancy

$$R_2 = \frac{\pi}{6} D_d^3 \rho_s g \tag{2}$$

where R_2——buoyancy
g——acceleration of gravity.

(3) Gravity

$$R_3 = -\frac{\pi}{6} D_d^3 \rho_d g \tag{3}$$

where R_3——gravity
ρ_d——droplet density.

(4) resultant force on the droplet is

$$R = R_1 + R_2 + R_3 \tag{4}$$

Substituting equations (1), (2) and (3) into equation (4) and applying Newton's Law, we get:

$$\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} + \frac{3\rho_s}{4\rho_d D_d}\zeta\left(\frac{\mathrm{d}z}{\mathrm{d}t} - U_s\right)^2 + g\,\frac{\rho_d - \rho_s}{\rho_d} = 0 \tag{5}$$

where the drag coefficient depends on Reynolds number.

Assuming that droplet motion conforms Stocks' law, it gives the drag as follows:

$$R_1 = -3\pi D_d \mu_s \left(\frac{\mathrm{d}z}{\mathrm{d}t} - U_s\right) \tag{6}$$

where μ_s——steam viscosity.

The equation (5), then, is reduced to:

$$\frac{d^2z}{dt^2}+\frac{1}{K_d\rho_d}(\frac{dz}{dt}-U_s)+g\frac{\rho_d-\rho_s}{\rho_d}=0 \tag{7}$$

where $K_d=\frac{D_d^2}{18\mu_s}$, called the diameter-viscosity term.

2.1.2 Droplet velocity is less than steam velocity

Similarly, when $U_{dz}<U_s$, the drag becomes:

$$R_1=\frac{\pi}{8}\zeta D_d^2\rho_s(U_s-\frac{dz}{dt})^2 \tag{8}$$

Equations (2) and (3) remain the same, so that the equation (5) becomes:

$$\frac{d^2z}{dt^2}-\frac{3\rho_s}{4\rho_d D_d}\zeta(U_s-\frac{dz}{dt})^2+g\frac{\rho_d-\rho_s}{\rho_d}=0 \tag{9}$$

Again, assuming that the droplet motion conforms Stocks' Law, gives the drag as follows:

$$R_1=3\pi D_d\mu_s(U_s-\frac{dz}{dt}) \tag{10}$$

This makes the equation (7) into:

$$\frac{d^2z}{dt^2}-\frac{1}{K_d\rho_d}(U_s-\frac{dz}{dt})+g\frac{\rho_d-\rho_s}{\rho_d}=0 \tag{11}$$

2.2 Solution of the momentum equation

2.2.1 When $U_{dz}>U_s$, taking the following combinations:

$m=g\frac{\rho_d-\rho_s}{\rho_d}$, $n=\frac{1}{K_d\rho_d}$, $D=nU_s-m$, reduces equation. (9) to the following:

$$\frac{d^2z}{dt^2}+n\frac{dz}{dt}=D \tag{12}$$

With the initial condition:

$t = 0 \qquad U_{dz} = U_d$

$t = 0 \qquad z = 0$

Where U_{dz}——axial component of droplet velocity；

U_d——droplet velocity at the exit of the primary separator.

Equation (12) is solved as

$$z = (U_s - \frac{m}{n})t + \frac{1}{n}(U_d - U_s + \frac{m}{n})(1 - e^{-nt}) \qquad (13)$$

Considering：

$t = t_1, \qquad U_{dz} = U_s$

the time for the droplet reaching the height H_1 is：

$$t_1 = \frac{1}{n}\ln\frac{nU_d - nU_s + m}{m} \qquad (14)$$

or ，when the droplet slows down until $U_{dz}=U_s$，the height is：

$$H_1 = \frac{1}{n}(U_s - \frac{m}{n})\ln\frac{nU_d - nU_s + m}{m} + \frac{U_d - U_s}{n} \qquad (15)$$

where H_1——the height of the space in which $U_{dz}>U_s$

2.2.2 when $U_{dz}<U_s$，taking the similar procedure gives the solution of equation (12) as follows：

$$z = U_s t - \frac{m}{n}t + \frac{m}{n^2}(1 - e^{-nt}) \qquad (16)$$

The time for a droplet rising from H_1 to H_2 is：

$$t_2 = \frac{1}{n}\ln\frac{m}{m - nU_s} \qquad (17)$$

or H_2 is the height where the droplet slows down from U_{dz} ($=U_s$) to U_{dz} ($=0$)，

$$H_2 = \frac{1}{n}(U_s - \frac{m}{n})\ln\frac{m}{m - nU_s} + \frac{U_s}{n} \qquad (18)$$

where H_2——the height where $U_{dz}<U_s$

2.2.3 The whole height which the droplet rises to in the gravity separation space is：

$$H = H_1 + H_2 = K_d\rho_d U_s\left\{\frac{U_d}{U_s} - (\frac{K_d\rho_d m}{U_s} - 1)\ln[1 + U_d(U_s(\frac{K_d\rho_d m}{U_s} - 1))^{-1}]\right\} \tag{19}$$

Where H——height needed for gravity separation space.

Substituting the reduced gravity acceleration $g' = g(1 - \frac{\rho_s}{\rho_d})$, slip ratio of two phases $S' = U_d/U_s$, terminal velocity of falling droplet $U_t = g'\rho_d K_d$, ratio $Q = U_d/U_t$, into equation (19), we obtain:

$$H = K_d\rho_d U_s[S' - (\frac{1}{Q} - 1)\ln(1 + S'(\frac{1}{Q} - 1)^{-1})] \tag{20}$$

Equation (20) indicates the droplet of a certain diameter and initial velocity U_d can rise to a height of H until it falls down or is separated.

If there is no slip between two phases, that is, $U_d = U_s$ or $S' = 1$, equation (20) is reduced to:

$$H = K_d\rho_d U_s[(\frac{1}{Q} - 1)\ln(1 - Q) + 1] \tag{21}$$

When the gravity separation height of a PWR steam generator is given, those droplets whose combined form K_d of diameter and viscosity exceeds the value of K_d as solved by equation (20) or (21), will be separated by gravity; vice verse, the droplets will be carried up into the dryer by the steam flow.

3 ENTRAINABLE DROPLETS

The minimum velocity of steam flow which can carry droplets to any height is called Droplet Carry-over Velocity (DCV). Taking use of a balance of gravity, buoyancy and drag as follows:

$$\frac{\pi}{4}D_d^2\rho_s\zeta\frac{U_{FS}^2}{2} = \frac{\pi}{6}D_d^3(\rho_d - \rho_s)g \tag{22}$$

can give an expression of DCV, U_{FS}

$$U_{FS} = 3.62\sqrt{\frac{D_d(\rho_d - \rho_s}{\zeta\rho_s}} \tag{23}$$

On the other hand, equation (23) can gvie the maximum diameter of those droplets which can be carried to any height. This maximum diameter is called Droplet Carry-over Diameter (D_{FS}) and the droplets whose diameter is less than D_{FS} are called Entrainable Droplets.

$$U_{FS} = 0.076 \frac{\zeta \rho_s U_s^2}{\rho_d - \rho_s} \tag{24}$$

It can be seen that increases in steam velocity or operating pressure can enhance the ability of steam flow to carry droplets. which adversely affect the steam water separation by gravity.

4 CONCLUSION

In this analysis of two phase separation by gravity, adoption of the momentum flow model and introduction of the combined term K_d of diameter and viscosity render the mathematical procedure simple and clear.

Stokes' Law is assumed for droplet motion in steam flow to make an analytical solution. If Stokes' Law is not complied with, the drag coefficients can be substituted into equation (5) or (9).

At the bottom of the gravity separation space, the initial kinetic energy of droplets depends on their exit velocity from the primary separator. If there is no two-phase slip, droplets then rise at the same velocity as steam, where as the steam velocity is related to the steam generator loading and the cross-section area of the steam generator upper shell.

Throughout the analysis, droplets take the spherical shape, which might not be the case all the time.

For the steam generator design with a large number of small primary separators, the assumption (4) may not result in a large error.

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