A simulation model for free surface oscillations effects on power stability of the Aqueous Homogeneous Reactor

Shuai Wang，Yingrui Yu，Liangzi Wang，Xue Qin, Zhumin Jiang

Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Chengdu, 610041, China

Abstract - Aqueous homogeneous reactor is character with fissile liquid fuel with free surface ,during operation,radiolytic gas bubbles breaking away the free surface will create oscillations,those oscillations motion and it's reflection off the reactor vessel complicate the free surface and change the fuel shape unceasingly,which may cause power instability.On the base of TCCAHR(Transient calculation Code of Aqueous Homogeneous Reactor),a model for free surface oscillations is developed:Oscillations amplitude change is defined by radiolytic gas bubbles volume change,this amplitude is used for define the mean density change on the free surface,the free surface oscillations are simplified to mean density change on the free surface.The operation simulation results of TRACY shows that:The free surface oscillations induce the power oscillations around a steady state,but not a power excursion.

I. INTRODUCTION

Aqueous homogeneous reactor is a kind of homogeneous reactor character with fissile liquid fuel and the mixing of fuel and moderator. In 1989, aqueous homogeneous reactor was proposed to be a Medical Isotopes Production Reactor (MIPR), which can produce ^{99}Mo efficiently and economically. This proposal kindles interests of many research institutes.

When operation in high power density, the radiolytic gas bubbles will form in the fuel and migrate to the free surface of the fuel solution, which will create waves. Those waves motion and its reflection off the reactor vessel complicate the free surface and change the fuel shape unceasingly, which may cause power instability.

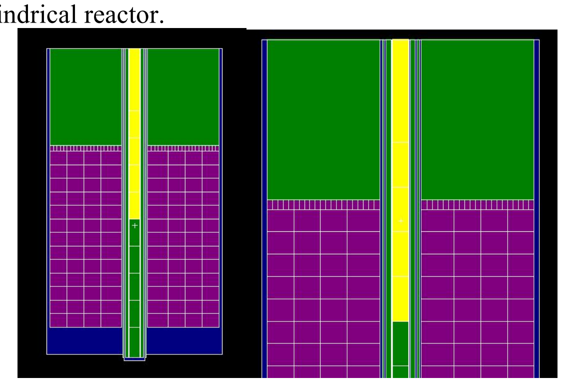
There are many literatures on the simulation of aqueous homogeneous reactor [2],[5-6], but little has considered the free surface oscillations. In the point kinetics model developed by C.M.Cooling [3], a model of free surface oscillations was proposed: this model provide a way to define the oscillations amplitude by radiolytic gas bubbles volume,but when comes to the geometry consider, it thought the sloshing of the liquid can be taken as continual change of surface geometries character with a height difference between the centre and the edge of the fuel,which is rather simple considering the complicate free surface of the aqueous homogeneous reactor.

Nuclear Power Institute of China (NPIC) developed the code TCCAHR(Transient Calculation Code of Aqueous Homogeneous Reactor) which based on the Monte Carlo method and improved quasi-static approximation method. This code includes the radiolytic gas bubbles model and thermal hydraulics feedback model, which make sure the high-accuracy simulation of the physics behavior of aqueous homogeneous reactor [1]. TCCAHR assume the free surface keep horizontal during operation and consider the volume change of reactor due to radiolytic gas production and thermal expansion, but doesn't consider the free surface oscillations. This study introduce a model which is capable of simulate the free surface oscillations effects on power stability of the aqueous homogeneous reactor to TCCAHR, and make the code a more reliable tool for the simulation of aqueous homogeneous reactor.

II.METHOD DESCRIPTION

Geometry consider

The TCCAHR divide the fuel solution into many fuel regions, for example: Figure 1(a) give the right view of geometry description for a cylindrical reactor TRACY, those purple regions are fuel regions,the green region is the upper air space, and there is a guide tube in the center containing a boron carbide control rod [5]. Figure 1(b) shows that a number of smaller fuel regions are divided in the free surface of the fuel in order to simulation the complicate free surface in different radial position. This model assume that the oscillations caused by radiolytic gas bubbles or reflections off the reactor vessel are within the scope of those small fuel regions,moreover,this model assume that those oscillations are ax symmetric in a cylindrical reactor.



(a) (b)

Figure. 1. Geometry consider of TRACY((a)Right view of geometry description of TRACY；(b)Small fuel regions in the free surface)

This model will simulate the free surface oscillations by density change of those small fuel regions,density change will affect cross section and the neutronics calculation.This simplification avoid those complicated geometry description of free surface oscillations,and we can continually update those density during the transient calculation,so as to learn the free surface oscillations effect on power stability of the aqueous homogeneous reactor.

Radiolytic gas bubbles

Once formed, the radiolytic gas bubbles will migrate to the surface vertically due to the buoyancy. TCCAHR treat the gas bubble volume in the fuel regions with a balance equation (Equation (1)) of volume changing rate, producing rate and removing rate.

$$\frac{\partial V_B(t,z)}{\partial t} = (1+\frac{1}{\xi})\frac{G(H_2)P(t,z)R_g T_g}{(X_w + \frac{2\alpha}{r_B})} - v(z)\frac{\partial V_B(t,z)}{\partial z} \quad (1)$$

Here $V_B(t,z)$ is the gas bubble volume of the fuel region, and $v(z)$ is the velocity of those gas bubbles.

TCCAHR demand user input for those parameters so as to calculate radiolytic gas bubbles volume distribution in the transient procedure.

Simulation of the oscillations

Those models for the sloshing simulation of fuel solution developed by C.M.Cooling[3] and the mathematical model for the prediction of wave motion in gas-agitated baths developed by M.P.Schwarz [4] shows that there are some factors can affect the oscillations:

(1) Oscillations change with a frequency.

(2) Oscillations amplified by the migration of the gas bubbles.

(3) Oscillations damped by effect of reactor vessel or other structure in the core.

Assuming the oscillations amplitudes are same on different place of free surface. The Oscillations can be define as:

$$\Delta z(t) = \frac{\int_0^H V_B(t,z)dz}{S} \quad (2)$$

$$\frac{d^2\phi}{dt^2} + w^2\phi = \theta_{osc}\frac{d\Delta z(t)}{dt} - \tau_{osc}\frac{d\phi}{dt} \quad (3)$$

Here ϕ is the oscillation; Equations (2) give the height change of the free surface caused by gas bubbles. H is the height of the fuel solution, S is the sectional area of the core. Equations (3) give of change rate of oscillations, w is the frequency of Oscillations. The first term of the right hand is the amplification by the migration of the gas bubbles, θ_{osc} is the amplification rate; the second term is the damping by effect of reactor vessel or other structure in the core, τ_{osc} is the damping rate.

Assuming the oscillations spread in the radial direction, an analytic solution for oscillations change is:

$$\phi(r,t) = \phi_0(t)\cos(2\pi(wt + r/l)) \quad (4)$$

Here l is the wavelength of oscillations; $\phi_0(t)$ is the oscillations amplitude.

For the small fuel region in the free surface with a height h , the oscillations occur in the scope of $\phi_0(t)$, the rest of region is without oscillations. So mean density of this region is $\rho(r,t)$:

$$\rho(r,t) = \rho_0\left(\frac{\phi(r,t)}{h} + \frac{h-\phi_0(t)}{h}\right) \quad (5)$$

Here ρ_0 is fuel density.

As the introduction,TCCAHR is based on Monte Carlo method and improved quasi-static approximation method. Fig. 2 shows the flowchart of TCCAHR.The time-space dependent neutron flux is divided into shape function which is varies slowly and amplitude function varies quickly.During the calculation, TCCAHR will continually update the radiolytic gas bubbles volume distribution,so as to update mean density of fuel regions on the free surface as well as other fuel regions for the amplitude function calculation,this procedure runs with high frequency, $\triangle t_m$ is time interval.

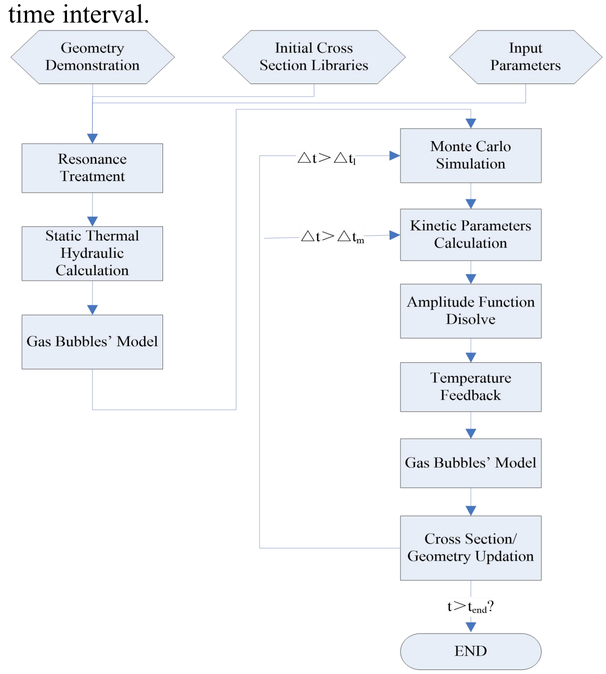


Fig. 2. Flow Chart of TCCAHR with Gas Bubbles' Model

$\triangle t_l$ in the Fig. 2 is time interval for calculation of shape function,TCCAHR will update the geometry description of the reactor core for the Monte Carlo simulation,this procedure runs with low frequency. Figure 3(a) shows the geometry description of TRACY simulation at a certain moment, the different color of fuel regions represent different density of fuel,we didn't consider the flow of the fuel,so there are more gas volume produce at the central of core which make the free surface height rise more at the central than at the edge of the core. Figure 3(b) shows the geometry description of free surface.

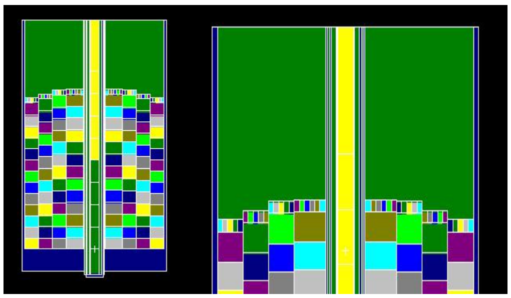


Figure. 3. Right view of geometry description of TRACY at t=20s

III.CALCULATIONS AND RESULTS

This improved TCCAHR with oscillations model was used for simulation of TRACY operation in a steady power, a comparing simulation was run without oscillations model.

Those parameters for Equation (1) shows in Table 1.

Those parameters for Equation (2) and (3) in Table 2.those parameters are closely related to the geometry of the reactor core,so it's very hard to confirm them without experiment data.some value of those parameters used by C.M.Cooling[3] are employed, for a qualitative analysis,and in order to reflect the disorder of free surface oscillations,we keep change the frequency of Oscillations by a random number from 0 to 1 .

Table 1. Summary of input parameters of TRACY for radiolytic gas bubbles model[1]

$G(H_2)/(mol/MJ)$	0.062
$1/\xi$	0.509
R_g	8.314
T_g/K	500
X_w/Pa	$1.013\cdot10^5$
$\alpha/(N/m)$	0.1
r_B/m	$5\cdot10^{-7}$
$v(z)/(m/s)$	0.05

Table 2. Input parameters of Equation 2 and 3

θ_{osc}	0.5[3]
τ_{osc}	0.07[3]
ω	Random number from 0 to 1

Figure. 4.shows calculated power history of TRACY by the TCCAHR with oscillations model. After normalizing the power according to the mean power, the Figure. 5. shows that there didn't appear obvious oscillation in power history if didn't consider oscillations model,power history is a straight line, but when those free surface oscillations are considered, the power of TRACY would oscillating around a steady power within a steady scope,but not a power excursion, which means, reaching a "quasi-steady-state", showing in figure 4 and Figure 5.

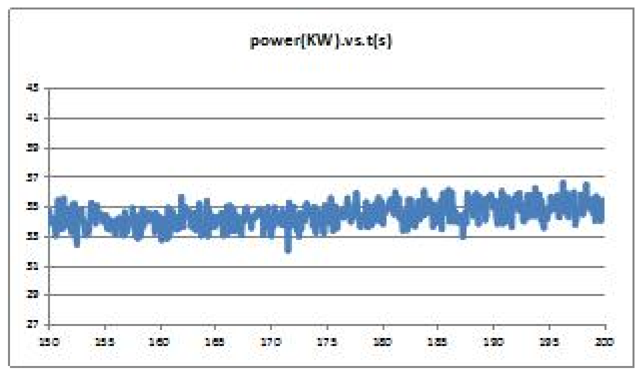


Figure. 4. The calculated power history of TRACY by the TCCAHR with oscillations model

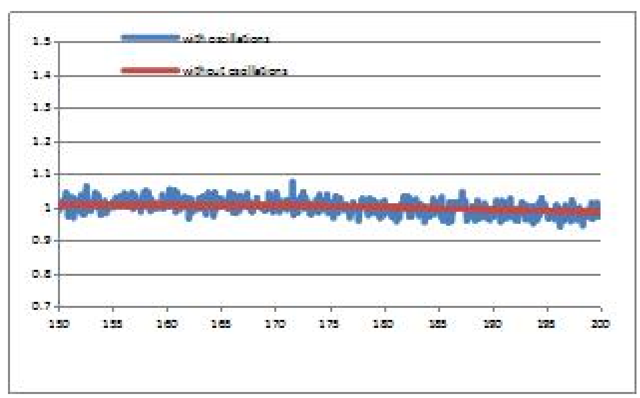


Figure. 5. The normalized power of TRACY.vs. time

IV.CONCLUSION

On the base of TCCAHR, a model for free surface oscillations effects on power stability is developed: Oscillations amplitudes are defined by radiolytic gas bubbles volume, those amplitudes are used to define the density change on the free surface. The free surface oscillations caused by radiolytic gas bubbles motion and waves and sloshing effects due to reflection off the reactor vessel walls are represented by mean density change on the free surface. Those steady operation simulations results of a aqueous homogeneous reactor show that:

The free surface oscillations induce the power oscillations around a steady state, but not a power excursion .

In the future,we will continually improve the TCCAHR code in some aspect,like analyze and confirm important parameters in free surface oscillations model,oscillations cause by the production of gas bubbles in the fuel and so on.

NOMENCLATURE

t=time
z=axial position of fuel region
$G(H_2)$=hydrogen yield in fuel solution
$1/\xi$ =fraction of other molecules per H_2 molecule produced by radiolysis
P(t,z)=power of the fuel region
R_g=gas constant
T_g=gas bubbles temperature
X_w=outside pressure
α=surface tension
r_B=radius of gas bubbles

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