Study on Start-up for NHR-5 Heating Reactor with ATHLET Code

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Abstract: nuclear reactor for urban residential heating or sea water desalination is an important field to expend peaceful application of nuclear energy. The simulation with general-purpose system simulation codes will play vital role for better understanding main thermal-hydraulic characteristics of the reactor proposed for heating or desalination. This paper reports a study on the start-up procedure of NHR-5, a pilot test heating reactor with 5MW thermal power at the institute of nuclear energy technology (INET) of Tsinghua University of China, with ATHLET code simulation. The effect of partial pressure of non-condensable nitrogen gas filled in the vapor chamber of the upper plenum to maintain PWR operation condition has been investigated. The results show that ATHLET code can produce reasonable solutions for exhibiting the intrinsic features of the start-up procedure of NHR-5.

KEYWORDS: heating reactor, start-up procedure, ATHLET code

I. Introduction
NHR-5 is a pilot test nuclear heating reactor with 5MW thermal power. This reactor was designed and constructed by the Institute of Nuclear Energy Technology of Tsinghua University in Beijing more than 10 years ago. The test operation of NHR-5 had been carried out intensively in a number of consecutive winter seasons from 1989 to 1993. The main technical and safety features of NHR-5 include: integral arrangement of the primary loop to eliminate large break loss of coolant accident, natural circulation of primary coolant flow, hydraulic-driven control rod system and pressurized water operation mode with inert gas of nitrogen filled in the upper part of the reactor vessel to maintain the sufficient subcooling in the primary loop for avoiding boiling in reactor core, the guard-vessel outside the reactor vessel to contain the primary coolant release due to over-pressure of the reactor vessel or small break of penetration pipes). The arrangement of the components inside the reactor vessel is shown in Fig.1. Many years test operation experience at INET has shown that NHR-5 test heating reactor is a super-safe nuclear facility satisfying all requirements to operate near the urban residential district according to the regulatory rules of China. All important safety features and operation procedures have been sufficiently demonstrated. Among the technical problems concerned in last decades, the start-up procedure of NHR-5 has also been investigated in detail, both experimentally and numerically.

The main purpose of this study is to assess the capability of ATHLET code developed by the research center of GRS (Gesellschaft Anlagen-und Reaktorsicherheit) at Garcing of Munich of Germany to run at low pressure condition and for a natural circulation system. This paper illustrates some simulation results from for system transient analysis.

II. ATHLET Code and Simulation Model
ATHLET is a general purpose thermal-hydraulic system simulation code package based on one-dimensional conservation equations for mass, momentum and energy balances. The code has been developed mainly for analyzing transient behavior of a nuclear power plant with a light water reactor, adopting both 5-equation drift flux model and 6-equation two-fluid model to describe two...
phase flow in a general fluid volume. Heat structure models for various geometries are used to simulate heaters, reactor fuel elements and heat exchangers. From past experience, the 5-equation drift flux model has been well validated and qualified by many benchmark problems. The conservation equations are summarized below.

Mass balance:
\[
\frac{\partial}{\partial t} (\rho_k u_k) + \frac{1}{A} \frac{\partial}{\partial z} (\rho_k u_k u_k A) = \Gamma_k
\]

Energy balance:
\[
\frac{\partial}{\partial t} (\rho_k h_k) + \frac{1}{A} \frac{\partial}{\partial z} (\rho_k u_k h_k A) = \alpha_k \frac{\partial p}{\partial t} + q_w + q_i + q_T + \Gamma_k h_k
\]

Momentum conservation:
\[
\frac{\partial G}{\partial t} + \frac{1}{A} \frac{\partial}{\partial z} \left( \frac{G_f^2}{(1-\alpha)} + \frac{G_g^2}{\alpha} \right) = \frac{\partial p}{\partial z} - F g
\]

The symbols in above equations are defined as:
\[
G = G_f + G_g = (1-\alpha) \rho_f u_f + \alpha \rho_g u_g
\]
\[
\rho = (1-\alpha) \rho_f + \alpha \rho_g
\]

The subscript \( k = f, g \) denotes respectively liquid phase and gaseous phase. Thermodynamic properties of \( \rho_k (p, h_k) \) for both phases can be obtained from steam table.

The interface jump conditions are:
\[
\Gamma_f + \Gamma_g = 0
\]
\[
\sum (q_a + \Gamma_d h_d) = 0
\]

ATHLET code applies Sonnenburg full-range drift flux correlation\(^5\) to define the relation between \( G_k \) and \( (G, \alpha) \).

Because NHR-5 is also a type of pressurized water reactor working at low pressure and natural circulation conditions, we expect that ATHLET code should be applicable to simulate flow transients in NHR-5 although validation work is required. One of the main goals of this study is to assess the applicability of ATHLET code for analyzing NHR-5 transients.

The simulation model of ATHLET code for the primary system of NHR-5 heating reactor is displayed by Fig. 2. The main geometric and operation parameters of NHR-5 test heating reactor are listed in table 1.

| Table 1: main parameters of the NHR-5 test heating reactor |
|---------------------------------------------|---------------------------------------------|
| Geometric parameters | Operation parameters |
| core height 0.69m | pressure \( p < 2.0 \)MPa |
| pitch 13.3 × 13.3mm | core inlet flow resistant coefficient 25 |
| outer diameter \( d = 10 \)mm | flow resistant coefficient of heat exchanger 84.7 × 2 |
| height of channeled chimney 0.99m | power < 5MW |
| height of common chimney 1.39m | - |

### III. Results and Discussions

The post-calculation to validate the ATHLET code has been carried out by comparing with operation records. Typical results for both steady state and power increase transient are shown in Fig. 3 and Fig. 4. These results have proven that the ATHLET code is capable of simulating NHR-5 behavior both qualitatively and quantitatively. More detailed assessment to the ATHLET simulation results in comparison with the NHR-5 test operation records has been accomplished recently\(^6\). All results satisfactorily support the validity of the ATHLET code for applying to NHR-5 heating reactor steady-state and transient analyses.
The start-up procedures for NHR-5 have been investigated with the validated ATHLET code and reported in this study. Three examples are given below.

1. Effect of the Partial Pressure of Nitrogen

The effect of the non-condensible gas mass (or partial pressure) of nitrogen filled in the reactor vessel to the start-up process of the NHR-5 is delineated by Fig. 5. The reactor core is simulated by electric heater so that other effects can be filtered out. The power increase has been controlled following a linear ramping up:

\[
Q(t) = Q_0,\text{hex} \frac{t}{\tau_0,\text{hex}}, \text{if } t < \tau_0,\text{hex} \quad \text{and} \quad Q(t) = Q_0, \quad \text{if } t \geq \tau_0,\text{hex} \quad (8)
\]

where \(Q_0,\text{hex}\) is the nominal full power of the main heat exchanger of the NHR-5 at steady state, here \(Q_0=5\) MW has been selected; \(\tau_0\) is the time duration with which the power increases from 0 level to the level of \(Q_0\), \(t\) is the time of the power rising.

The results have shown that the partial pressure of the non-condensible is of significant effect to the start-up transient of NHR-5 heating reactor. With the increase of the partial pressure of the non-condensible, the start-up transient becomes smoother. When the partial pressure of nitrogen reaches 0.6 MPa, the start-up transient will no longer encounter an unstable flow region. The results indicate that at high partial pressure of nitrogen, the pressure increases with the power level climbing up in the reactor vessel prevails to the reduction of subcooling margin of the fluid to prevent it from boiling. Therefore, the start-up transient of natural circulation in the reactor vessel exhibits stable characteristics. At low partial pressure of nitrogen, the change of system pressure is somehow directly related to the saturation temperature of the vapor and the additional overpressure to suppress boiling is also low. If the power increase is faster than the extracted heat power from the heat exchanger, then the subcooling of the flow will reduce and the boiling or sub-cooled boiling is easier to take place in the system.

2. Point Kinetic Core Model and Electric Heater Model

The comparison of the code simulations using a point kinetic model with 6-groups of delayed neutrons embedded in ATHLET and applying the model with electric heater to emulate the reactor core is reported here. The nuclear fuel rod model in ATHLET code is selected as the heat structure model when neutron kinetic effect is taken into account. The neutron kinetic parameters, such as delayed neutron fraction, lifetime of neutron generation and the decay time constant of precursors from which the delayed neutrons are generated, are obtained from the detailed reactor physics design with CASMO-3/SIMULATE-3 code package for NHR-5. Assuming the NHR-5 initially is at near-zero power and at hot state (~160 °C), the power increase of the reactor core is controlled by heat extraction rate from the main heat exchanger by means of negative reactivity feedback coefficient which is also given by detailed reactor physics design. This study employs the following equation to describe the heat power extracted from the primary system of the NHR-5 heating reactor by into the secondary loop:

\[
Q(t) = Q_0,\text{hex} \frac{t}{\tau_0,\text{hex}}, \text{if } t < \tau_0,\text{hex} \quad \text{and} \quad Q(t) = Q_0, \quad \text{if } t \geq \tau_0,\text{hex} \quad (9)
\]

where \(Q_0,\text{hex}\) is the nominal full power of the main heat exchanger of the NHR-5 at steady state; \(\tau_0,\text{hex}\) is the time duration with which the power increases from 0 level to the level of \(Q_0\), \(t\) is the time of the power increasing.

3. Effect of the Time Constant of the Power Extraction

The effect of the time constant \(\tau_{0,\text{hex}}\) of the power extraction shown in Eq. (9), is also investigated with the point kinetic model simulation and the results are displayed in Fig. 7. With the reduction of the time constant of the heat power extraction in the start-up transient, the inlet temperature of the reactor core decreases faster, resulting in a stronger positive reactivity or power increase. The driving head of natural circulation is going to enhance faster due to stronger heat addition in the reactor core, so that the flow transient behavior exhibits much higher overshoot at the initial stage. Therefore, the ATHLET code can reasonably describe the performance of the NHR-5 heating reactor with a large negative temperature reactivity coefficient.

IV. Conclusions

ATHLET simulation models for the NHR-5 pilot
nuclear test heating reactor with and without considering nuclear feedback have been established respectively. Both models are applied to investigate the start-up transient. The effect of the partial pressure of the non-condensable nitrogen filled in the vapor chamber of the upper plenum of the reactor vessel to the start-up transient has been investigated. The comparison of both ATHLET simulation models has been carried out by adopting the same power increase history in the model with electric heater as that in the model with point kinetic nuclear feedback model. The influence of the time constant describing the speed of heat extraction from the primary system of the NHR-5 heating reactor has also been investigated.

The numerical simulation results have indicated that by increasing partial pressure of the filled non-condensable gas, the stable PWR start-up process can be established. The minimum partial pressure of non-condensable for establishing stable PWR start-up transient has been numerically found. The numerical simulation has also implied that stable conversion from PWR operation mode to BWR operation mode is attainable by degassing non-condensable filled in the reactor vessel at near saturation temperature corresponding to partial pressure of water vapor and at zero power level.

The comparisons of the results from both models with and without nuclear feedback description have shown that if the power increase transient can be well presented, the thermalhydraulic behavior of the NHR-5 heating reactor in the start-up transient can be well simulated by both models with ATHLET code. The comparisons imply that ATHLET code thermalhydraulic model is applicable to investigate the natural circulation of a system similar to the NHR-5 heating reactor.

The influence of the time constant describing the speed of heat extraction from the primary system of the NHR-5 heating reactor shown by ATHLET code simulation results has reflected the correct tendency of the nuclear kinetic model of ATHLET code.

Although the results presented in this paper are based on ATHLET code simulation, the conclusions drawn from analysis results are quite consistent, at least qualitatively, with both the NHR-5 test operation experience and the simulated experimental study\(^7,^8\).

**Nomenclatures**

**Symbol**

A: flow area  
F: flow resistance force  
G: mass flux  
g: gravitational acceleration  
h: enthalpy  
p: pressure  
q: volumetric heat release rate  
Q: heat power  
t: time  
u: flow velocity  
W: mass flow rate  
z: coordination along flow loop  
α: void fraction  
ρ: density  
f′: phase mass generation  
τ: time duration to increase power  

**Subscript**

f: liquid phase  
g: gas/vapor phase  
hex: heat exchanger  
i: interface  
w: wall  
υ: flow dissipation  
0: steady state

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**References**


Fig. 5 Effect of non-condensable partial pressure
Initial conditions: $p=0.81\,\text{MPa}$, $W=0\,\text{kg/s}$, $T_0=170.41^\circ\text{C}$;
(a) $p_N=0\,\text{MPa}$; (b) $p_N=0.1\,\text{MPa}$; (c) $p=0.4\,\text{MPa}$

Fig. 6 Effect of the time constant of heat extraction rate with $Q_{0,\text{hex}}=2.985\,\text{MW}$
Initial conditions: $p=1.093\,\text{MPa}$, $T_0=161.25^\circ\text{C}$, $W=0\,\text{kg/s}$
(a) $\tau_{0,\text{hex}}=4000\,\text{s}$; (b) $\tau_{0,\text{hex}}=100\,\text{s}$
Fig. 7 Comparison of the Results from both ATHLET Simulation Models with or without Nuclear Feedback Models, $Q_{0,hex}=2.985$ MW

Initial Conditions: $p=1.093$ MPa, $T_0=161.25^\circ$C, $W=0$ kg/s

(a) with Point Kinetic Model; (b) without Nuclear Feedback Model

(Reactor power $Q(t)$, inlet/exit temperature $T_{in}/T_{ex}$ and mass flow rate $W$ from top down)