Calculation model of non-nuclear steam rush in steam turbine of nuclear power unit Construction and application

Junfeng Liu, Zhen Kang, Miaomiao Wang, Shima Chao, Jingbin Xi, Zhijun Wu, Wei Wang and Zhenlu Zhang

[1] Xi'an Thermal Power Research Institute Co.,Ltd, Xi'an 710000, China
[2] Huaneng Nuclear Energy Technology Research Institute co., ltd, Shang Hai 200126, China
[3] Jiangsu Nuclear Power Co., Ltd, Lian Yungang 222042, China.

Abstract. According to the technical characteristics of steam turbines and their thermodynamic systems of various types of nuclear power units, a calculation software suitable for evaluating the feasibility of non-nuclear steam rushing of steam turbines of various types of nuclear power units is developed The software can accurately evaluate and check the non-nuclear steam rushing parameters by comparing the steam intake and heat consumption required by the steam turbine with the effective steam quantity and heat storage provided by the primary loop, and solve the quantitative evaluation problem of the feasibility of non-nuclear steam rushing for steam turbines of various types of nuclear power units.

Keywords: Nuclear power unit; Turbine rushing; Non-nuclear vapor; Thermodynamic model.

1. Introduction

At present, the installed capacity and technical level of nuclear power units in China have developed rapidly Because the third and fourth generation advanced nuclear power units under construction have adopted a large number of new technologies, new processes and new equipment, the construction period of nuclear island lags behind that of conventional island, and there is still enough time to carry out the first impulse test of turbo-generator unit before the first critical test of reactor Therefore, it is necessary to use non-nuclear steam for the first rotary test of turbo-generator set to find out and deal with the problems existing in turbo-generator set as soon as possible, so as to realize the seamless connection between nuclear island and conventional island commissioning test and shorten the construction period to the maximum extent[1-6].

Regarding the evaluation of the feasibility of non-nuclear steam run-in, literature [1] proves that it uses non-nuclear steam through the theoretical analysis and calculation of the comprehensive heat balance between the nuclear steam supply system and the steam turbine generator system before and after run-in of the AP1000 nuclear power steam turbine generator It is feasible to conduct the first run-through test of steam; literature [2] started from the first law of thermodynamics, established the calculation formula of non-nuclear run-in balance, and clarified the feasibility of non-nuclear steam run-in of turbogenerator units, and conducted the test in Unit 1 of Fuqing Nuclear Power Plant Successfully implemented; literature [3] based on the technical characteristics of the pebble bed modular high-temperature gas-cooled reactor, carried out comprehensive heat balance calculations for the two methods of heat storage in the primary circuit and steam supply from the auxiliary boiler, and obtained a feasible non-nuclear steam flushing scheme . Due to the large differences in the steam turbines of various types of nuclear power units, pressurized water reactors and fast reactor nuclear power units generally use half-speed steam turbine generators, and high-temperature gas-cooled reactors use full-speed steam turbine generators. The calculation methods in the existing literature are all limited to the selection of flushing steam parameters considering the characteristics of their own units, and there is no calculation model suitable for comprehensively evaluating the feasibility of non-nuclear steam flushing of various types of nuclear power units. This paper intends to establish a quantitative evaluation calculation model applicable to the feasibility of non-nuclear steam flushing of steam turbines of various types of nuclear power. units.

2. Thermodynamic Model

To realize non-nuclear steam flushing of nuclear power unit, two necessary conditions must be met: (1) there is enough steam intake to make the turbo-generator set rise from zero speed (turning speed has little influence) to rated speed; (2) There is enough heat storage of non-nuclear steam to meet the heat consumption of turbo-generator set during empty load test under impulse and rated speed This research results establish the thermal balance model diagram of turbo-generator set as shown in Figure 1 below.

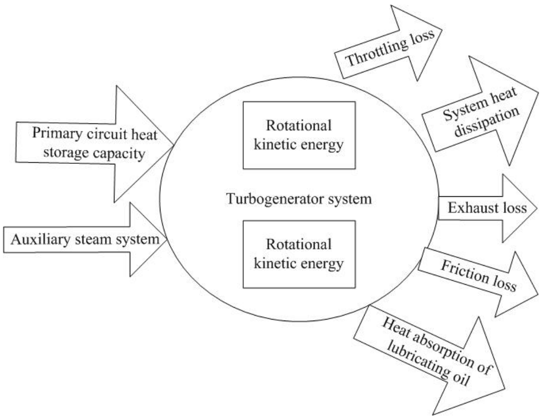

Fig. 1 Heat balance model diagram of turbo-generator set

2.1 Flushing Steam Intake

According to the pressure and temperature given by the steam turbine manufacturer, the inlet steam pressure and temperature under rated working conditions and the rated flow rate, the steam flow rate during the rushing period can be calculated by Friuger's formula:

$$\frac{q}{q_0}=\sqrt{\frac{T_0}{T}}\sqrt{\frac{P_1^2-P_2^2}{P_{1,0}^2-P_{2,0}^2}} \tag{1}$$

Where: q is the main steam flow rate, kg/s; T is the grade group temperature, ℃; P is the stage group pressure, MPa;; Subscript 0 indicates the known standard working condition (rated working condition) parameter, subscript 1 indicates the parameter before the stage group and subscript 2 indicates the parameter after the stage group.

During the process of steam turbine rising from zero speed to rated speed, the relationship between inlet steam flow and time is approximately linear When $t \geq t\ 0$, the steam quantity required for steam turbine rushing is:

$$m=\frac{1}{2}\times q\times t_0+q\times(t-t_0)=q\times(t-\frac{t_0}{2}) \tag{2}$$

Where: m is the amount of steam, kg; t is the total time s of non-nuclear steam rush and test, s; t_0 is duration from zero speed to rated speed, s.

2.2 Heat Consumption of Steam Turbine

From the heat balance model diagram of turbo-generator set in Fig. 1, it can be seen that the heat consumed during the period when the turbo-generator set is driven up to the rated speed by the rotational kinetic energy provided by the primary loop heat storage during the rush period includes heat absorption system of steam turbine metal body, heat dissipation, throttling, exhaust steam and friction loss, heat absorption of lubricating oil and steam supply heat of shaft seal The heat of each part is calculated separately below .

According to the kinetic energy theorem, the rotational kinetic energy of the rotor that should be input after the rotor of the turbo-generator set reaches the rated speed is as follows:

$$Q_1=\frac{1}{2}\times GD^2\times\omega^2=\frac{1}{2}\times GD^2\times(\frac{2\pi n}{60})^2 \tag{3}$$

Where: GD^2 is the moment of inertia of the entire turbine generator shafting, kg·m^2; ω is the angular velocity, rad/s; n is the rotational speed, r/min.

Metal components such as rotor stator blades and cylinder diaphragm will absorb part of steam heat during steam turbine rushing. The total heat absorption of metal is:

$$Q_2=c_1 m_1(T_2-T_1) \tag{4}$$

Where: c_1 is the specific heat capacity of metal, J/(kg °C); m_1 is metal mass, kg; T_1 and T_2 is the initial temperature and equilibrium temperature of metal,℃.

Most of the steam inlet modes of steam turbines in nuclear power plants adopt throttling regulation. The throttling loss mainly comes from the steam inlet loss of steam turbine regulating valves under different overlapping degrees. The calculation formula is as follows:

$$Q_3=\sum_{i=1}^{n} q_i(H_{1,\ i}-H_{2,\ i})\ t \tag{5}$$

Where: q_i is the steam inlet flow rate of nozzles between stages of each regulating valve ,kg/h, H is the steam enthalpy value , kJ/kg; Subscript 1 indicates the parameters before the steam inlet nozzle and subscript 2 indicates the parameters after the steam inlet nozzle; i is the number of nozzles from 1 to n.

The heat dissipation of turbo-generator system mainly comes from the heat dissipation of thermal insulation materials laid on the cylinder surface to the environment, which can be obtained by Fourier heat conduction law:

$$Q_4=A\frac{\lambda}{\delta}(T_3-T_4)t \tag{6}$$

Where: λ is the thermal conductivity ,W/(m • K); A is heat exchange area, m2; δ is the thickness m of thermal insulation material, m; T_3 and T_4 are the temperature of the inner and outer sides of the insulation material , ℃.

Exhaust steam loss is caused by friction swirl in the process of exhaust steam flow from the last stage rotor blade and then into the condenser through the exhaust pipe The calculation formula of pressure loss of exhaust pipe is:

$$\Delta p=\frac{q_1^2\nu_1}{A_1^2}\left[(\zeta_{ex}-1)\frac{1}{f^2}\right] \tag{7}$$

According to the concept of thermal equivalent, the heat loss of exhaust steam can be obtained as follows:

$$Q_5=\Delta pV=\frac{q_1^2\nu_1}{A_1^2}\left[(\zeta_{ex}-1)\frac{1}{f^2}\right]V \tag{8}$$

Where: q_1 is the final exhaust mass flow rate, kg/s; ν_1 is the specific volume of steam after the last rotor blade, m^3/kg; A_1 is the inlet area of exhaust pipe,m^2; ζ_{ex} is the loss coefficient of exhaust pipe; f is the diffuser of exhaust pipe, that is the ratio of inlet and outlet areas of exhaust pipe; V is exhaust pipe volume， m^3

The friction loss in the process of steam turbine rushing comes from the bearing part and the generator part, and the friction loss is as follows:

$$Q_6 = \int_0^t T_r \frac{d\omega}{dt} t \qquad (9)$$

The friction torque of each radial bearing is:

$$T_r = \frac{4\mu F_r D_r}{2\pi} \qquad (10)$$

Radial loads are:

$$F_r = k_r m_2 g \qquad (11)$$

Where: T_r is the friction resistance moment of radial bearing; μ is the friction factor of bearing contact surface; F_r is the radial load N acting on the radial bearing，N; D_r is the diameter m at the contact surface of radial bearing，m; Kr is the radial load coefficient of the rotor, and the value is 0.5; m_2 is the rotor mass,kg; g is the acceleration of gravity and the value is 9.8 m/s2

Heat absorption of steam turbine lubricating oil is:

$$Q_7 = c_2 m_2 (T_5 - T_6) \qquad (12)$$

Where: c_2 is the specific heat capacity of lubricating oil, J/(kg ° C); m_2 is the mass of lubricating oil ,kg; T_5 and T_6 are the return temperature and inlet temperature of lubricating oil,℃

Turbine shaft seal steam supply from auxiliary steam system shaft seal steam supply high pressure cylinder and low pressure cylinder shaft seal and finally flow into steam turbine generator set exhaust steam The heat provided is:

$$Q_8 = q_2 t\ (H_1 - H_2) + q_3 t\ (H_3 - H_2) \qquad (13)$$

Where: q_2 and q_3 are the inlet steam flow rates of high pressure cylinder and low pressure cylinder , kg/s; H_1、H_2 and H_3 are the inlet and exhaust enthalpy of high pressure cylinder and inlet enthalpy of low pressure cylinder, kJ/kg.

Based on the above, the total heat consumption of steam turbine can be obtained:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 - Q_8 \qquad (14)$$

2.3 Primary circuit heat storage

Only when the effective steam quantity and heat storage quantity provided by the primary loop are greater than the steam intake quantity and heat consumption required by the steam turbine for impulse rotation can the demand of impulse rotation and empty load test be met The main systems for heat exchange in the primary loop of PWR nuclear power unit during impulse rotation include main pump coolant regulator and its electric heating system steam generator pressure vessel core and chemical and volumetric control system The main systems for heat exchange in the primary circuit of HTGR unit include main helium blower helium coolant steam generator pressure vessel pebble bed core and internals The main systems for heat exchange in the primary circuit of fast neutron reactor unit include sodium pump in the primary circuit, sodium coolant in the secondary circuit, sodium pump, buffer tank, steam generator and superheater Through the system design data, the effective heat supply provided by the primary circuit of the above types of nuclear power units is checked respectively, and the effective steam supply in the impact test time is calculated $Q_{\text{Thermal storage}} > Q$, $m_{\text{Steam}} > m$,The primary heat storage generated by the primary power source (main pump or main fan) can meet the requirements of the non-nuclear impulse test of the steam turbine of the nuclear power unit When any condition exists, the auxiliary steam should provide additional heat to raise the feed water temperature of the secondary loop or pass the auxiliary steam into the steam generator for heat exchange to increase the heat storage capacity of the primary loop, so that the heat storage capacity of the primary loop can finally meet the requirements of the non-nuclear steam rush test.

3. Computing Software Development

3.1 Software Development Process

The software is edited by using the MODULE module of matlab programming language The data input module, steam turbine inlet flow calculation module, steam turbine heat consumption calculation module, primary loop heat storage calculation module, impulse parameter checking and selection module and post-processing module are constructed in C/C + + programming language environment The relationship between the modules and the software calculation flow are shown in Figures 2.

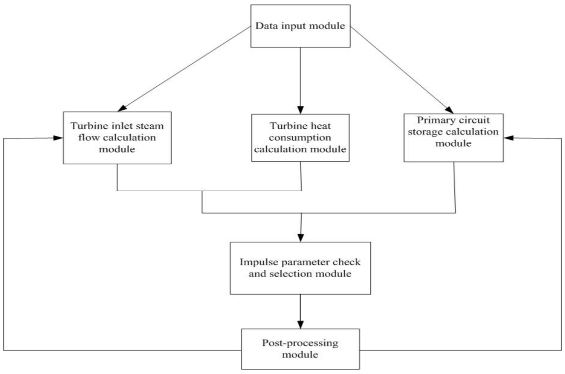

Fig. 2 Software Module Composition

3.2 Software function module

The data input module includes technical parameters of various types of nuclear power plant steam turbines such as pressurized water reactors, fast reactors, and high-temperature gas-cooled reactors. It has the functions of query, addition, modification, and deletion, which is convenient for the next step of fast and accurate thermodynamic calculations. It also has software expansion functions. The steam turbine inlet steam flow calculation module and the steam turbine heat consumption calculation module respectively calculate the rush rotation by the software calculation process shown in Fig. Inlet steam flow and heat consumption required for the test. The primary circuit thermal storage module includes three core sub-modules of pressurized water reactor, fast reactor and high-temperature gas-cooled reactor. heat storage. The check and selection module of the running parameters compares the intake steam flow and heat consumption obtained by the above modules with the heat storage of the primary circuit. If the heat storage of the primary circuit does not meet the running demand, start the auxiliary steam supply steam source check calculation program , and get the selection of parameters that meet the conditions of the reversal, and then re-check the calculation until the optimal thermodynamic parameters of the reversal are selected. The post-processing module includes a data summary, printing module and curve drawing module, which can realize data collection and online printing, and convert the result data into intuitive graphics to express through ORIGIN, TECPLOT and other drawing software.

4. Example validation

According to the technical standard given by the steam turbine manufacturer, the main equipment test parameters of primary and secondary circuits before and after non-nuclear steam flushing are shown in Table 1 below.

Table 1 Non-nuclear steam impulse test parameters of primary and secondary circuit main equipment

Status parameters	Initial value of test	End value of test
Pressurizer level/m	0.96	-3.94
Pressurizer pressure/MPa	15.5	15.3
Pressurizer power/kW	1440	0
Pressurizer temperature/°C	291.4	255
Main pump power/kW	5734	0
Steam generator water level/m	0.18	-0.76
Steam generator pressure /MPa	7.6	4.3
Steam generator temperature /°C	291.4	255

According to the above technical parameters of the primary circuit and steam turbine of the nuclear power unit, the calculation results of the thermodynamic model of the software are analyzed and compared with the actual impact results as shown in Table 2 below

Table 2 Calculation and test values of non-nuclear steam impact

parameters	Model calculation value	Test value
Test time/min	70	68.75
Primary circuit provides heat storage /kJ	2.09×10^8	2.2×10^8
Effective steam volume/t	85.21	82.15
Steam turbine impulse heat consumtion/kJ	1.9×10^8	1.81×10^8
Steam turbine impulse starting steam intake /t	80.26	80.18

From the calculation results in Table 2, it can be seen that the deviation rate between the model calculation value and the actual value is in the range of 1% ~ 5%. Considering that there is a certain heat loss in the primary loop system during the actual ramping process and there is a deviation between the actual heat consumption and the designed heat consumption value of the steam turbine, the deviation rate is within the allowable range of calculation error

5. Conclusion

In this paper, C/C++ language is used to compile the non-nuclear steam rushing calculation software of the steam turbine of the nuclear power unit, and the calculation software of the non-nuclear steam rushing and heat consumption of the steam turbine of the nuclear power unit is obtained. The software consists of a data input module, a steam turbine inlet steam flow calculation module, It consists of six basic modules: steam turbine heat consumption calculation module, primary circuit heat storage calculation module, flush parameter check and selection module, and post-processing module. Through engineering examples, it is verified that the computing software structure design is appropriate, the architecture is stable, the scalability and reusability are good, the reliability and accuracy meet the requirements, and it has certain engineering application value.

References

1. Chen Biyun, Li Xintong, Li Bin, etc. Feasibility Analysis and Calculation on Initial Startup of an AP1000 Nuclear Power Unit with Non-nuclear Steam [J]. Journal of Chinese Society of Power Enigineering 2014, 34 (11): 915-919，920.
2. Xiao Bo, He Liu . Feasibility Analysis and Optimization for Turbo-Generator Rushing with Non-Nuclear Steam in Fuqing Nuclear Power Plant [J]. Nuclear Power Engineering 2018，39（3）：122-127.

3. LIU Junfeng，CHEN Zhigang，GAO Jinghui, etc. Feasibility Analysis on Impulse Starting of HTR-PM Nuclear Power Unit with Non-Nuclear Steam [J]. Thermal Turbine 2018，47（4）：293-295，308.
4. Bao Xudong. Startup Practice of Non-nuclear Steam of 1 089 MW Nuclear Turbine Generating Unit [J]. Zhejiang Electric Power 2016，35（6）：57-60.
5. TANG Mei-yu,HE Zhao-hui.Initial Startup of Qinshan II 650MW Nuclear Unit with Non-nuclear Steam[J]. Turbine Technology2005，47（2）：142-144，146.
6. Zhang Yabo，Zhang Donghui. The first rushing of CEFR turbine [J]. Chinese Journal of Nuclear Sciences and Engineering 2010，30（1）：19-24.