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Research on characteristics of varying conditions for nozzle governing stage based on dimensional analysis

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ABSTRACT

In this paper, thermodynamic calculations of nozzle governing stage are taken based on APROS (Advanced Process Simulation), and verify through the comparison of experiment table data. The influence of partial admission on pressure ratio within the governing stage is also analyzed. The results show that partial admission not only leads to partial admission losses, but also makes an impact on pressure ratio, enthalpy and reaction degree, in turn, causes the change of efficiency. Then, the nozzle pressure ratio after the full-open valve and semi-open valve respectively, is expressed as a function of flow ratio based on dimensional analysis. This paper presents a method of thermodynamic calculation for nozzle governing stage. Comparing with the results calculated through APROS and discussing the change of pressure ratio and reaction degree, it shows that the method can reflect the influence of partial admission on pressure ratio exactly, and further improve the accuracy of existing thermodynamic calculation.

1. Introduction

Nozzle governing units often operate under part-load conditions during most of their working time in accordance with the fluctuation of power supply [1,2], resulting in the governing stage running at the partial admission condition. Although it is helpful to improve the operated economy of part-load conditions, it also brings partial admission losses [3,4]. Therefore, it is necessary to further study the influence of partial admission on the governing stage characteristics, which has important guiding significance to operation optimization, technological innovation and energy-saving of the unit.

At present, much research has been done for this issue. Ref. [5] studied on the working mechanism of partial admission through the experiment table test, and approached the influence of partial admission losses on thermal economy. It is also observed that the difference in the micro-turbine heat rate was no higher than 10% at the same partial load. Ref. [6] aimed at three-dimensional unsteady flow of the governing stage through the numerical simulation. The results indicated that the pressure gradient after the rotor blade changed from circumference to axial when the rotor blade rotated through the blockage area of the governing stage, causing the output of rotor blade declined. Ref. [7] did a further research on clearance vibration force of the governing stage, and established the force model of the rotor blade tip, then the influence of partial admission on steam flow vibration force was also analyzed by the calculation with different admission modes.

From the perspective of thermodynamic calculation, the existing methods usually determine partial admission losses to reflect their influences on the governing stage efficiency. Since partial admission leads to the nonuniformity distribution of aerodynamic parameters [8], errors exist between calculated results and actual operation. Thus, further improvement is needed for thermal calculation of the governing stage.

2. The establishment of model

The calculation of varying conditions for the governing stage is highly complex, for the working processes of steam flow must be considered with two parts, namely the work fluid pass through the full-open control valve and the semi-open control valve, respectively.

Due to more stages and lower back pressure, the entire stages after the governing stage can be taken as a stage group [9]. According to Frugal formula, the steam mass flow G_1 of the governing stage, the pressure p_{21} and temperature T_{21} after the governing stage during variable operation can be expressed:

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Nomenclature

G_1	steam mass flow of the governing stage under varying condition, kg/s
G	steam mass flow of the governing stage under design condition, kg/s
p_{21}	pressure after the governing stage under varying condition, MPa
p_2	pressure after the governing stage under design condition, MPa
T_{21}	temperature after the governing stage under varying condition, K
T_2	temperature after the governing stage under design condition, K
v_{21}	specific volume after the governing stage under varying condition, m^3/kg
v_2	specific volume after the governing stage under design condition, m^3/kg
G'_n	steam mass flow of the full-open valve, kg/s
p_0	pressure in front of the valve, MPa
v_0	specific volume in front of the valve, m^3/kg
A'_n	area of the nozzle group after the full-open valve, m^2
β'_n	flow ratio of the nozzle group after the full-open valve
G'_{cn}	critical steam mass flow of the nozzle group after the full-open valve, kg/s
ε_{n1}	pressure ratio of the nozzle group
ε_{cr}	critical pressure ratio of the nozzle group
μ	flow coefficient
ε	pressure ratio of the governing stage
G''_n	steam mass flow of the semi-open valve, kg/s
p'	pressure after the semi-open valve, MPa
A''_n	area of the nozzle group after the semi-open valve, m^2
β''_n	flow ratio of the nozzle group after the semi-open valve
G''_{cn}	critical steam mass flow of the nozzle group after the semi-open valve, kg/s
ε_{n2}	pressure ratio of the nozzle group

$$G_1 = G\frac{p_{21}}{p_2}\sqrt{\frac{T_2}{T_{21}}} \tag{1}$$

where G_1, p_2, T_2 are separately steam mass flow, pressure and temperature of design condition.

In order to improve the accuracy, equation (1) can be modified:

$$G_1 = G\sqrt{\frac{p_{21}}{p_2}\cdot\frac{v_2}{v_{21}}} \tag{2}$$

where v_2 and v_{21} are steam specific volume after the governing stage of design condition and varying conditions respectively.

2.1. The full-open control valve

With the control valve fully open, the steam mass flow G'_n, which flow through the nozzle group after the full-open valve, can be calculated [9]:

$$G'_n = 0.648A'_n\beta'_n\sqrt{p'_0/v'_0} \tag{3}$$

$$G'_n = \frac{0.648A'_n}{\sqrt{p_0v_0}}\cdot\frac{\beta'_n}{p_{21}/p'_0}\cdot p_{21} = A'\mu'p_{21} \tag{4}$$

$$\beta'_n = \frac{G'_n}{G'_{cn}} = \sqrt{1-\left(\frac{\varepsilon_{n1}-\varepsilon_{cr}}{1-\varepsilon_{cr}}\right)^2} \tag{5}$$

$$\varepsilon_{n1} = p_{11}/p'_0 \tag{6}$$

where $A' = 0.648A'_n/\sqrt{p_0v_0}$, $\mu' = \beta'_n/p_{21}/p'_0$; p_0 and v_0 are pressure and specific volume in front of the valve, respectively; p'_0 and v'_0 are pressure and specific volume after the full-open valve, respectively; A'_n is nozzle group area of the full-open valve; β'_n is flow ratio of the nozzle group; G'_{cn} is critical steam mass flow of the nozzle group; ε_{n1} is pressure ratio of the nozzle group; ε_{cr} is critical pressure ratio of the nozzle group, for the superheated steam, $\varepsilon_{cr} = 0.546$.

According to equation (5), with certain structural parameters, ε_{n1} can be seen as a function of G'_n. G'_n changes with G_1, which is the steam mass flow of the governing stage under varying conditions. Taking G as a reference, which is the steam mass flow of the governing stage under design condition, ε_{n1} can be assumed that:

$$\varepsilon_{n1} = CG_1^{k_1}G^{k_2} \tag{7}$$

where C, k_1 and k_2 are all coefficients.

Since ε_{n1} presents dimensionless quantity, the right side of equation (7) is also non-dimension according to the dimensional analysis theory [10], namely $k_1 + k_2 = 0$. Equation (7) can be inverted:

$$\varepsilon_{n1} = C\left(\frac{G_1}{G}\right)^k \tag{8}$$

The thermodynamic calculations of the governing stage are performed on a 600 MW nozzle steam turbine based on APROS (Advanced Process Simulation) (constant pressure operation and the closing sequence of the control valve is GV4 (Governing Valve 4)—GV3—GV2—GV1), which compare with the conventional calculations without considering the influence of partial admission on pressure ratio within the governing stage. The action of GV4, for example, the relationship between ε_{n1} and G_1/G is shown in Fig. 1.

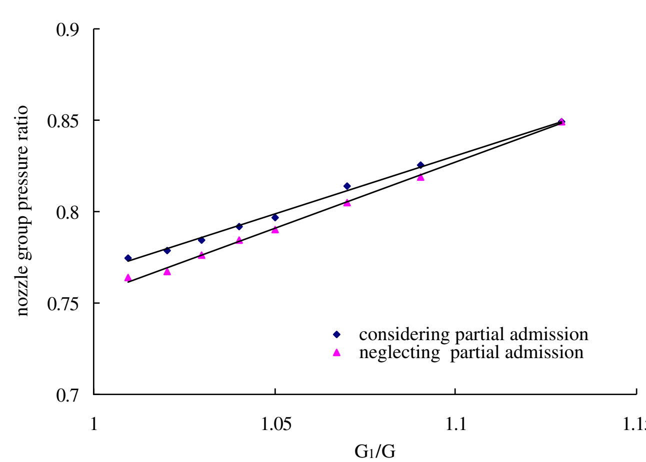

Fig. 1. Nozzle group pressure ratio vs flow ratio after the full-open valve.