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# Numerical investigation on the self-excited oscillation of wet steam flow in a supersonic turbine cascade*

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**Abstract** The self-excited flow oscillation due to supercritical heat addition during the condensation process in wet steam turbine is an important issue. With an Eulerian/Eulerian model, the self-excited oscillation of wet steam flow in a supersonic turbine cascade is investigated. A proper inlet supercooling results in the transition from steady flow to self-excited oscillating flow in the cascade of steam turbine. The frequency dependency on the inlet supercooling is not monotonic. The flow oscillation leads to non-synchronous periodical variation of the inlet and outlet mass flow rate. The aerodynamic force on the blade varies periodically due to the self-excited flow oscillation. With the frequency lies between 18.1—80.64 Hz, the oscillating flow is apt to act with the periodical variation of the inlet supercooling due to stator rotor interaction in a syntonic pattern, and results in larger aerodynamic force on the blade. The loss in the oscillating flow increases 20.64% compared with that in the steady flow.

**Keywords:** **self-excited oscillation, wet steam, turbine cascade, condensation.**

Steam turbine plays an important role in the power generation industry. The wet steam flow in large-scale condensing steam turbine and nuclear steam turbine not only degrades the efficiency, but also leads to water erosion of the blade, which puts negative effect on the safety of the steam turbine. The self-excited oscillation is one type of special phenomenon in wet steam flow. It was firstly discovered by Schnerr1) in 1962 in slender nozzle flow of moist air. Then in 1970 the self-excited oscillation in pure steam flow was reported by Barschdorff and Filippov[1]. The self-excited oscillation is caused by the interactions between the condensation process and local supersonic flow in wet steam.

In the one-dimensional flow, heat addition makes the flow Mach number approach to the unit. For the supersonic flow with Mach number $M_a$, the critical amount of heat $Q_c$ is required to return the flow to sonic condition. In the isentropic flow in convergent-divergent nozzle, the flow in downstream of the throat is supersonic; however in the condensing flow, the heat release during condensation process in the divergent part of the nozzle returns the supersonic flow to sonic condition, even to subsonic condition. For a given nozzle, the condensation process and the amount of heat addition $Q$ to the supersonic flow are determined by the inlet flow conditions. Subcritical heat addition ($Q < Q_c$) will result in a small pressure rise, the so-called "condensation shock", and the flow is stable. For supercritical heat addition ($Q \geqslant Q_c$), an aerodynamic shock is embedded in the zone of rapid condensation, which is located in the downstream of the throat, and the flow is stable. In condition $Q \gg Q_c$, the aerodynamic shock moves upstream even close to the throat of nozzle. As a result, the temperature before the rapid condensation zone rises, and the condensation intensity is weakened, then with the decreased heat release the condition leading to aerodynamic shock is broken. The supercooling in the condensing flow rises once more, and the above cycle repeats.

It can be seen that the self-excited oscillation is caused by the interactions between the condensation process and the local supersonic flow in wet steam. Such condition exists in wet steam turbine; therefore the self-excited flow oscillation is also likely to happen in steam turbine. Dobkes et al.[2] conducted measurements on the stress of the rotor blade in an experimental steam turbine. They found that when the un-

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1) Schnerr B. Beobachtungen über das verhalten der durch wasserdampfkondensation ausgelösten störungen in einer überschall-windkanaldüse. Dissertation, Uniersität Karlsruhe (TH), 1962, Germany.

steady flow is observed in the turbine cascade, the stress of the rotor blade increases 1.5—2 times. It was concluded that the self-excited oscillation in the turbine cascade takes place. Whirlow et al.[3] observed non-synchronous rotor blade vibrations in a steam turbine, which may also be attributed to condensation induced oscillation in part of the cascade passage.

For steam turbine, the self-excited oscillation not only leads to vibration of blade, but also produces additional losses besides the well-known non-equilibrium loss, such as the aerodynamic shock loss due to supercritical heat addition and that caused by separation of boundary layer interacting with aerodynamic shock.

The progress in study of the self-exited oscillation in wet steam turbine is slow for the complex nature of this problem. Few experimental results were published. Some researchers conducted numerical simulations[4—6]. However, most published papers were limited to the study on the unsteady flows in nozzles. Investigation on the oscillating flow in steam turbine still requires more efforts. In this paper, the stable limit of the wet steam flow and the self-excited oscillation in a supersonic turbine cascade are numerically studied. The effects of flow oscillation on the aerodynamic performance of the cascade and the characteristics of the blade strength are also discussed.

## 1 Mathematical model

The condensing flow of wet steam can be treated as a two-phase system: the water vapor in the mixture of wet steam is the gaseous phase, and the liquid phase is the collection of all the condensate water droplets dispersed in the wet steam. For the homogeneous condensation in the transonic flow of wet steam, the diameter of water droplet is smaller than 1 μm. Therefore it is reasonable to neglect the velocity slip between the water droplets and the water vapor, and an Eulerian/Eulerian model can be established. The conservation equations of mass, momentum, and energy for the wet steam are

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g U) = -\rho \dot{m}, \qquad (1)$$

$$\frac{\partial(\rho_g U)}{\partial t} + \nabla \cdot (\rho_g U U) = -\nabla p + \nabla \cdot \Pi - \rho \dot{m}\, U, \qquad (2)$$

$$\frac{\partial \rho_g E_g}{\partial t} + \nabla \cdot (\rho_g E_g U) = -\nabla \cdot p U + \nabla \cdot \Pi \cdot U - \rho \dot{m}\,(h_t - h_{fg}), \qquad (3)$$

where $\rho_g$ is the density of the water vapor, $\rho$ the density of the mixture of wet steam, $U$ the velocity vector, $p$ the static pressure, $E_g$ the total energy, $h_t$ the total enthalpy and $h_{fg}$ the latent heat. The source terms $-\rho\dot{m}$, $-\rho\dot{m}\,\boldsymbol{U}$ and $-\rho\dot{m}\,(h_t - h_{fg})$ are introduced to count the interactions between the gaseous and liquid phases. Here $\dot{m}$ is the condensate mass rate and expressed as

$$\dot{m} = (1 - Y) J \rho_1 \frac{4\pi r_c^3}{3} + 4\pi r^2 \frac{dr}{dt} \rho_1 N, \qquad (4)$$

where $\rho_1$ is the density of water. The nucleation rate $J$ and the droplet growth rate $\frac{dr}{dt}$ are determined by the classical condensation theory and the same expressions as published in Ref. [4] are adopted. In addition, the Virial equation for water vapor is employed to make the equation set enclosure.

$$p = \rho_g R T (1 + B\rho_g + C\rho_g^2). \qquad (5)$$

In the above expression, $B$ and $C$ are the second order and third order Virial coefficient respectively.

As noted previously, the velocity slip between the gaseous phase and liquid phase can be neglected, so only additional equations describing the quantity and size of droplets are required for the liquid phase. Let $N$ denote the number of water droplets, $r$ the radius, and $Y$ the condensate mass fraction. The conservation law yields

$$\frac{\partial(\rho N)}{\partial t} + \nabla \cdot (\rho N U) = \rho_g J, \qquad (6)$$

$$\frac{\partial(\rho Y)}{\partial t} + \nabla \cdot (\rho Y U) = \rho \dot{m}. \qquad (7)$$

After $N$ and $Y$ are solved, the radius $r$ can be determined by the following equation

$$r = \sqrt[3]{3Y/(4\pi\rho_1 N)}. \qquad (8)$$

Now, with Eqs. (1)—(3) and (6)—(8) the wet steam flow with non-equilibrium condensation can be solved. The finite volume method and the explicit time-marching technique are used. The second-order upwind scheme is adopted in the spatial discretization. The dual time stepping method is applied for the time dependent problem.

## 2 Validation of the model

The condensing flow with self-excited oscillation in a convergent-divergent nozzle was simulated to validate the numerical model. Skillings et al.[5] conducted experimental investigation on the condensing flow in the nozzle. The geometry of the nozzle is showed in Fig. 1. The throat is located at $x=0$. Three positions marked as 1, 2 and 3 were set to record the pressure time history. The axial distances from these points to the throat are 0, 91 and 30 mm respectively. The flow conditions are: the total pressure $p_t=35140$ Pa, the total temperature $T_t=347.9$ K, and the flow at the exit section is supersonic. The grid number is $200\times 60$.

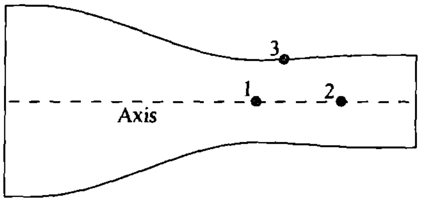

Fig. 1. Nozzle geometry.

The pressure distribution along the axis is showed in Fig. 2. It can be seen that the flow is oscillating in the rapid condensation zone immediately downstream the nozzle throat, which is caused by the interactions between the condensation process and the local supersonic flow as described previously.

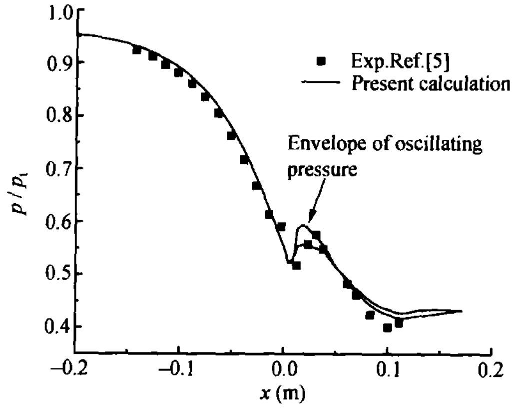

Fig. 2. The distribution of pressure along the axis.

The time history of pressure on points 1, 2 and 3 is showed in Fig. 3. The frequency $f$ of the oscillating flow is given by the FFT (Fast Fourier Transform) analysis and listed in Table 1. The calculated frequency is 382.17 Hz, which agrees well with the experimental value 380 Hz. The amplitude $\Delta p$ of the oscillating pressure in the rapid condensation zone is also listed in Table 1. The experimental value on point 3 is 2000 Pa, and the numerical simulation gives 2034.93 Pa. It can be seen that the numerical model properly predicts the characteristics of the self-excited flow oscillation in this nozzle.

Table 1. The characteristics of oscillating flow on point 3

| | $f$ (Hz) | $\Delta p$ (Pa) |
|---|---|---|
| Exp.[5] | 380.00 | 2000.00 |
| Cal. | 382.17 | 2034.93 |

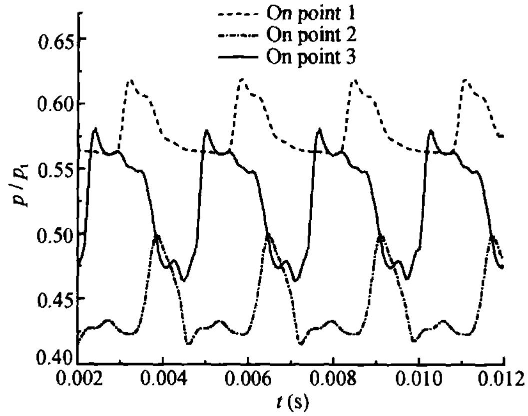

Fig. 3. Time history of pressure in the nozzle.

## 3 The self-excited flow oscillation in a supersonic turbine cascade

In large-scale steam turbine, the flow in the low-pressure turbine stages is often in supersonic condition near the blade tip. As noted previously, the self-excited flow oscillation is also likely to take place in supersonic turbine cascade. With the numerical model in section 1, the oscillating flow in a supersonic turbine cascade is investigated. The geometry of the cascade is given in Fig. 4. Three points marked as 1, 2 and 3 in the divergent part of the cascade passage are set to monitor the oscillation parameters.

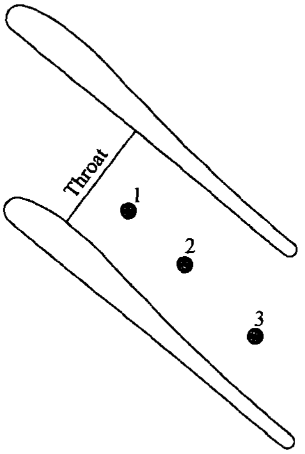

Fig. 4. Geometry of the supersonic turbine cascade.

### 3.1 The steady limit

Calculations were firstly implemented to determine the steady limit of the wet steam flow in this cascade. Keeping the pressure ratio $p_b/p_t = 0.38$ constant ($p_b$ is the downstream pressure of the cascade), the inlet supercooling $\Delta T$ increases from $-0.8$ K to 6.1 K, and the flow in the supersonic cascade transits from steady to oscillating.

The dynamics of the self-excited flow oscillation for the supersonic cascade is given in Fig. 5. As described previously, the self-excited oscillation in wet steam flow is a result of supercritical heat addition. When the inlet supercooling $\Delta T$ is smaller than 1.1 K, the heat release in the condensation process is smaller than the required critical heat addition and the flow is steady. With the increase of inlet supercooling, the self-excited oscillation takes place. It can be seen that the frequency dependency on the inlet supercooling is not monotonic. An increase of inlet supercooling from 1.1 K to 3.1 K results in a decrease of the frequency from 36.6 Hz to 18.1 Hz. After this point the frequency increases to 80.64 Hz when the inlet supercooling increases to 6.1 K.

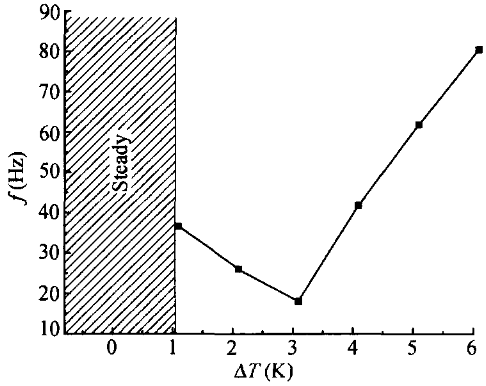

Fig. 5. Dynamics of self-excited flow oscillation for supersonic cascade.

### 3.2 The effects of self-excited flow oscillation

In this section, the self-excited flow oscillation with $\Delta T = 6.1$ K is discussed. In order to clearly evaluate the effects of the oscillating flow, the results are compared with those in the steady flow with $\Delta T = -0.8$ K. The following discussion is limited to these two flow conditions.

In Fig. 6 the time history of Mach numbers on points 1, 2 and 3 (see Fig. 4) is showed for the oscillating flow. It can be seen that the Mach numbers on point 1 and 2 are fluctuating between supersonic and subsonic conditions, which is a typical characteristic of the self-excited oscillation in wet steam flow caused by the supercritical heat addition. A FFT analysis gives the frequency $f = 80.64$ Hz.

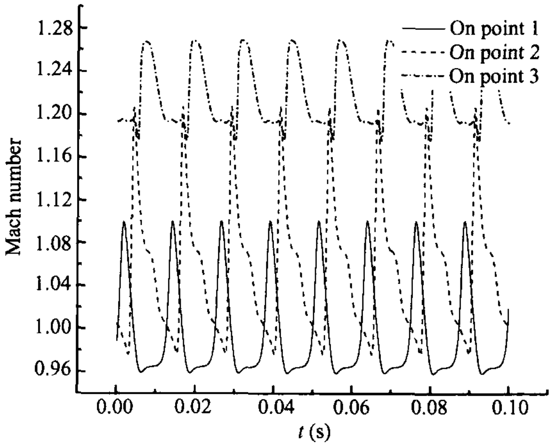

Fig. 6. Time history of Mach number in the cascade.

Due to the periodical variation of the Mach number above and below unit at the throat section, it can be inferred that the mass flow rate is varying periodically accordingly. Supposing that the cascade has unit spanwise height, the time history of mass flow rate is showed in Fig. 7. The periodical subsonic condition at the throat section allows the oscillating pressure in the rapid condensation zone to spread upstream. As a result, the inlet mass flow rate varies periodically. Though the time-averaged mass flow rates at the inlet section and outlet section are identical, the variations of mass flow rate at these two sections are not synchronous. The difference indicates the periodical compression and expansion of wet steam in the cascade passage.

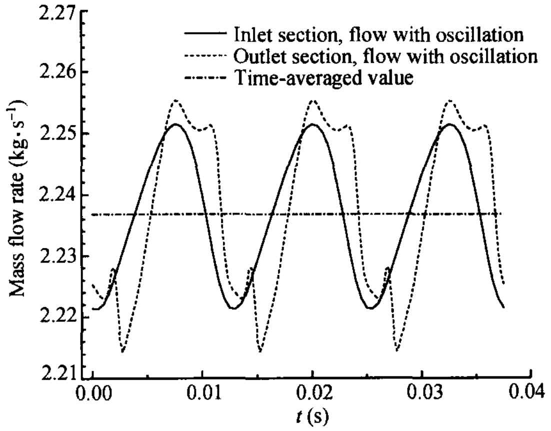

Fig. 7. Time history of mass flow rate.

The effect of flow oscillation on the blade stress in the wet steam flow is of interest from the view of blade safety. Fig. 8 gives the aerodynamic force on the blade exerted by the oscillating flow supposing that the cascade has unit spanwise height. The axial force $F_x$ and the tangential force $F_y$ in a cycle are plotted in this figure and compared with that in the steady flow. The aerodynamic force in the steady flow is 759.68 N; the maximum and the minimum of the aerodynamic force in the oscillating flow are 788.50 N and 741.04 N respectively. The force on the blade is periodically varied though the amplitude is small compared with that in Ref. [2] mentioned previously. It is worth noting that the present investigation was conducted on a single cascade, whereas the measurement in Ref. [2] was implemented in the turbine stages of an experiment steam turbine. Due to the effect of wakes behind stator blades, the temperature at the inlet section of rotor is periodically varying, therefore the inlet supercooling in rotor cascade varies accordingly relative to the angular speed of the rotor, and the oscillating characteristic in the rotor cascade may change essentially. For a rotor with angular speed 3000 rpm, the frequency of the inlet supercooling is 50$n$ Hz ($n$ is the blade number) for the rotor cascade. On the other hand, the frequency of the self-excited flow oscillating lies between 18.1—80.64 Hz according to the present results. It is possible in a turbine stage that the periodical variation of the inlet supercooling due to the stator rotor interaction acts with the self-excited oscillation caused by the supercritical heat addition in a syntonic pattern, thus larger oscillating aerodynamic force on the rotor blade will be obtained.

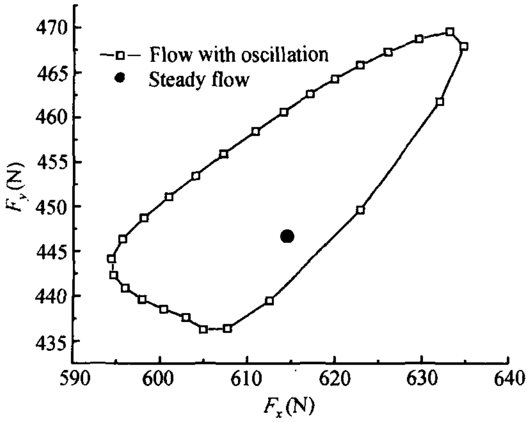

Fig. 8. The aerodynamic force on the blade.

In Fig. 9 the entropy increase is given. The entropy increase for the steady flow is 28.05 J/(kg·K), and the time-averaged value for the oscillating flow is 33.84 J/(kg·K). The loss in the self-excited oscillating flow increases about 20.64% compared with that in the steady flow.

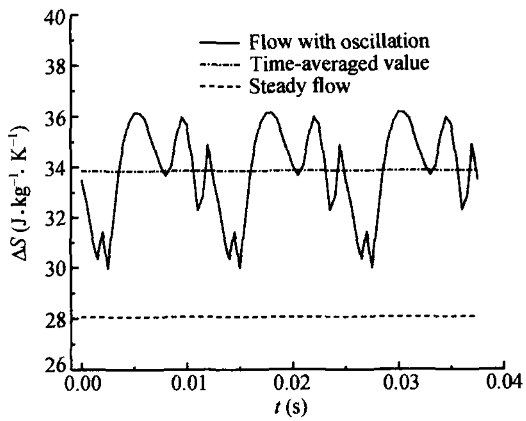

Fig. 9. Entropy increase.

## 4 Conclusions

An Eulerian/Eulerian model has been developed to investigate the unsteady wet steam flow with nonequilibrium condensation. With this model, the self-excited flow oscillation in a supersonic turbine cascade is investigated.

The supercritical heat addition during the condensation process leads to unstable flow. With proper inlet supercooling the steady wet steam flow transits to self-excited oscillating flow. The frequency dependency on the inlet supercooling is not monotonic. The flow oscillation results in periodical variation of the mass flow rate and the aerodynamic force on the rotor blade, which put negative effect on the blade safety. The entropy increase in the self-excited oscillating flow is obviously higher than that in the steady flow.

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