Acid Corrosion Analysis in the Initial Condensation Zone of a H₂O/CO₂ Turbine

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Abstract: A supercritical H₂O/CO₂ turbine is a key piece of equipment for the coal gasification in the supercritical water (CGSW) cycle to achieve conversion of heat into power. Compared with a traditional steam turbine, the working medium of an H₂O/CO₂ turbine has a relatively high CO₂ concentration. In the initial condensation zone (ICZ), steam condenses into droplets on the turbine blades and the droplets combine with CO₂ to form carbonic acid, which corrodes the turbine blades. In order to research the characteristics of acid corrosion in the ICZ of a H₂O/CO₂ turbine, the acid corrosion rate of the blades in the ICZ of the H₂O/CO₂ turbine was calculated and analyzed based on the three-dimensional CFD (3D CFD) method and a one-dimensional numerical model of CO₂ corrosion. The results suggest that acid corrosion rates decrease stage by stage in the ICZ due to the reduction in temperature and pressure. Rotor blades in the first stage in the ICZ suffer the worst and form a corrosion zone at the trailing edge of the blade and on the pressure surface. The decline of efficiency caused by corrosion settles down to a relatively steady value of 0.6% for a 10 year service time. Moreover, the corrosion area for the last two stages shrinks with the service time due to the rearward movement of the ICZ.

Keywords: H₂O/CO₂ turbine; initial condensation zone; acid corrosion; numerical simulation; performance degradation

1. Introduction

Coal plays an important role in the worldwide energy structure, especially in the Asia-Pacific region [1]. However, the burning of coal causes non-negligible waste and inescapable of pollution due to its large amount of emissions consisting of NOₓ, SO₂ and CO₂. Innovation has a positive effect on greenhouse gas emission reduction in major economies such as the European Union, China and the United States of America [2]. A novel cycle called coal gasification in supercritical water (CGSW) has been proposed by Guo et al. [3]. In this cycle, the traditional burning process is displaced by a coal gasification process in supercritical water, ultimately generating a mixture of vaporous water and carbon dioxide (H₂O/CO₂). It is economic and clean, and is therefore a highly potential new approach for the future of coal utilization.

Supercritical (about 600 °C and 25 MPa at the inlet) H₂O/CO₂ turbines are critical equipment for the CGSW cycle and are needed to accomplish the conversion of heat into power. H₂O/CO₂ turbines work in a fluid with a relatively high CO₂ concentration (the mass fraction of CO₂ is about 10–12% in the working medium), which is much higher than traditional steam turbines. In the initial condensation zone (ICZ), steam condenses into droplets on the turbine blades and the droplets combine with CO₂ to form carbonic acid which has moderate corrosiveness [4]. For turbomachinery, corrosion will directly result in geometrical deviations of the blades and lead to performance degradation [5]. Stress...
corrosion cracking (SCC) and corrosion fatigue will also occur in these low-pressure stages, and this degrades the safety and reliability of the turbine [6].

Relevant studies on the corrosion characteristics of steel in a CO$_2$-H$_2$O system are mainly in the field of oil and gas or CO$_2$ transport pipelines. These fields have already drawn a lot of researchers, scholars and engineers who have researched the mechanisms and the influencing factors of CO$_2$ corrosion, including temperature [7,8], CO$_2$ partial pressure [9–11], flow speed [12,13] and pH value [14,15]. Tanupabrungsun [16] proposed a mechanism for CO$_2$ corrosion, where the temperature ranged from 25 °C to 250 °C. It was suggested by de Waard et al. [17] that the corrosion rate increased with temperature because of the acceleration of the kinetic rate of the electrochemical reactions under 80 °C. Guo et al. [18] suggested that the corrosion rate did not change with temperatures in the range of 90–125 °C due to the formation of protective FeCO$_3$. Choi et al. [19] cleared up the interaction of pressure on the solubility of CO$_2$ and concluded that the solubility of carbon dioxide increased rapidly to a certain value and then slowly increased with pressure. Wei [20] investigated the effect of flow on the corrosion rate and found that the flow velocity intensified the corrosion rate by affecting the formation of corrosion product films. Nesic [21] suggested that pH affected the corrosion rates directly (via the reduction of H$^+$ ions) and indirectly (via the formation of corrosion product films), and that a system was more corrosive with a lower pH.

A variety of CO$_2$ corrosion models have been proposed and are extensively used in academic research and industrial applications. On the basis of dependence on theoretical foundations, existing models are divided into three categories: empirical/semi-empirical models, elementary mechanistic models and comprehensive mechanistic models [22]. Empirical/semi-empirical models are generally simple tools for the prediction of corrosion. In most cases, these models are mathematical functions which are developed from experimental data with no actual basis in physics meanings or theoretical foundations. Thus, these models are not applicable to new data sets and cannot be reliably extrapolated for an environment beyond the conditions in which they are developed. To overcome the abovementioned disadvantages, elementary mechanistic models are developed based on the theories of electrochemistry, chemistry and mass transfer. These models [23,24] have a true theoretical meaning and are adapted to a variety of corrosion conditions. On the basis of the elementary mechanistic model, comprehensive mechanistic models were established to more realistically describe major processes involved in a corroding system. Turgoose et al. [25] proposed a comprehensive model based on the transfer equations and the homogeneous reaction equilibria of carbonate species in diffusion layers. Pot [26] proposed a model in which charge transfer rates are assumed to follow the Tafel equation. In more extensive studies by Nesic et al. [27] and Nordsveen et al. [28], the Nernst–Planck equation was employed to describe the mass transfer of species in a solution. Additionally, the concentration of species on a metal surface is considered instead of bulk concentration.

Flow parameter distribution in the ICZ of H$_2$O/CO$_2$ turbines is necessary for predicting corrosion rates. The three-dimensional CFD method can be used for flow field simulation and predicting the aerodynamic performance of a turbine. A H$_2$O/CO$_2$ turbine design methodology was developed by Zhang et al. [29] and includes an optimal preliminary design method, a quasi-one dimensional (Q1D) performance analysis module, a reliable and efficient property table of the H$_2$O/CO$_2$ mixture and a 3D CFD simulation strategy. Cao [30] adopted a method to predict the performance of compressors with different corrosion degrees whereby different roughness values are added to the surfaces of blades by using a wall function.

CO$_2$ corrosion characteristics vary under different corrosion environments. Although considerable research on CO$_2$ corrosion has been conducted, at present, to the authors’ knowledge, there are few studies on CO$_2$ corrosion in the ICZ of H$_2$O/CO$_2$ turbines. To ensure the reliability and performance of H$_2$O/CO$_2$ turbines under CO$_2$ corrosion conditions, it is of great importance to study acid corrosion properties in the ICZ of H$_2$O/CO$_2$ turbines and to explore the influence of corrosion on these turbines. Corrosion
occurs in the ICZ of the low-pressure parts of the H$_2$O/CO$_2$ turbine. Therefore, the working medium of the turbines is at a subcritical state in this study.

2. Corrosion Model and CFD Method

In this study, a CO$_2$/H$_2$O turbine blade corrosion prediction system was developed, as shown in Figure 1. Based on the designed supercritical H$_2$O/CO$_2$ turbine, 3D CFD simulations were performed to determine the corrosion environment. Then, parameters such as temperature, pressure and velocity were used to calculate the corrosion rate with a CO$_2$ corrosion model. Next, the surface roughness values caused by corrosion were added to the blade surface, and 3D CFD simulations with different surface roughness were carried out to predict the aerodynamic performance at different service times. Details of the corrosion model and CFD method are described below.

![Flowchart of the developed corrosion prediction system.](image)

2.1. Corrosion Model

The CO$_2$ corrosion phenomenon of turbine blades occurs in the initial condensation zone of supercritical H$_2$O/CO$_2$ steam turbines. In the ICZ, steam condenses into water droplets as a result of a decrease in temperature and pressure as working fluid flows toward the rear stages. Afterwards, CO$_2$ dissolves in condensed water to form carbonic acid. Specifically, the dissociation of CO$_2$ and the formation of carbonic acid occur on the turbine blades, and the carbonic acid corrodes the blades. To predict the corrosion rate succinctly and efficiently, a one-dimensional acid corrosion model was established in this study to calculate the CO$_2$ corrosion. This model contained mass transport, chemical reactions and electrochemical reactions. The computational region of the model is shown in Figure 2. The thickness of the boundary layer was based on Reynolds number. The diffusion and turbulent sublayers were variable and correlated with the mass transfer parameters. A turbulent diffusivity term was added to the diffusion coefficient to build the turbulent sublayer. The term was determined by the viscosity, flow rate, density of the liquid and the distance from the steel surface [28]. All the compounds and ions were assumed to be diluted in the solvent and the mass transfer process was described by diffusion. This corrosion model was integrated into an extension based on the COMSOL Multiphysics software (v5.3a, COMSOL Inc., Stockholm, Sweden).

2.1.1. Mass Transfer Model

The concentration field of the CO$_2$-H$_2$O system consisted of CO$_2$, H$_2$CO$_3$, HCO$_3^-$, CO$_3^{2-}$, H$^+$, OH$^-$ and Fe$^{2+}$ and was solved by a mass transfer model. In this study, the flux of species $i$ is described by Fick’s first law:

$$N_i = -D_i \nabla c_i,$$

where $N_i$ (mol·m$^{-2}$·s$^{-1}$), $D_i$ (m$^2$·s$^{-1}$) and $c_i$ (mol·m$^{-3}$) are mass flux, diffusion coefficient and concentration of the specific species $i$, respectively. The diffusion coefficients of dissolved substances in the reactive system are listed in Table 1.
Figure 2. Description of the computational region of the corrosion model.

Table 1. Modeled species with their respective diffusion coefficients.

| Species    | Diffusion Coefficient (m² s⁻²) | Reference |
|------------|---------------------------------|-----------|
| CO₂        | 1.96 × 10⁻⁹                    | [28]      |
| H₂CO₃      | 2.00 × 10⁻⁹                    | [28]      |
| HCO₃⁻      | 1.11 × 10⁻⁹                    | [28]      |
| CO₂⁻       | 0.92 × 10⁻⁹                    | [28]      |
| H⁺         | 9.31 × 10⁻⁹                    | [28]      |
| OH⁻        | 5.26 × 10⁻⁹                    | [28]      |
| Fe²⁺       | 0.72 × 10⁻⁹                    | [28]      |

Afterward, mass conservation of each species is expressed as follows:

$$\frac{\partial c_i}{\partial t} + \nabla \cdot \mathbf{J}_i = R_i$$

(2)

where $R_i$ (mol m⁻² s⁻¹) is the production/consumption rate of species $i$ arising from chemical reactions in the reaction media.

The concentration of CO₂ in the solvent is solved according to Henry’s law. The Henry constant of CO₂ at varied temperatures is estimated by the formula shown below:

$$K_{CO₂} = 0.0454 \times 1.6616 - 5.736 \times 10^{-2}(T - 273) + 1.031 \times 10^{-3}(T - 273)^2 - 9.68 \times 10^{-6}(T - 273)^3 + 4.471 \times 10^{-8}(T - 273)^4 - 7.912 \times 10^{-11}(T - 273)^5$$

(3)

Chemical reactions in a CO₂-H₂O system include CO₂ hydration and two sequential dissociation steps of H₂CO₃, as well as water dissociation which was taken into account in this model. Corresponding chemical equilibrium constants are available in Table 2.

Table 2. Chemical reactions in the corrosion system and their equilibrium constants.

| Chemical Reaction | Equilibrium Constant | Reference |
|-------------------|----------------------|-----------|
| H₂O ⇔ H⁺ + OH⁻    | 10⁻²(29.3868 - 0.0375497 + 7.4781 × 10⁻³T) | [28]      |
| CO₂ + H₂O ⇔ H₂CO₃ | 2.58 × 10⁻³           | [31]      |
| H₂CO₃ ⇔ HCO₃⁻ + H⁺ | 387.6 × 10⁻¹(6.41 - 1.994 × 10⁻³T) + 8.52 × 10⁻⁴T² - 3.07 × 10⁻⁶P - 0.4772² + 0.1187 | [32]      |
| HCO₃⁻ ⇔ CO₂⁻ + H⁺  | 10⁻⁶(10.61 - 4.97 × 10⁻³T) + 1.331 × 10⁻⁵T² - 2.624 × 10⁻³P - 1.166² + 0.34667 | [32]      |

2.1.2. Electrochemical Model

Generally, the time scale of potential distribution in an electrochemical system is much smaller than the mass transfer. For water systems, any small charge separation will produce a significant potential gradient which tends to rapidly restore the system to the state of
electroneutrality. Consequently, in this study, an assumption of local electroneutrality was made.

The electrode surface boundary feature was adopted to solve the corrosion potential on the blade surfaces using the mixed potential theory. The total current density of all electrochemical reactions was set to 0, which leads to the following equation:

$$\sum j i_j = 0,$$

(4)

where $i_j$ (A·m$^{-2}$) is local current density of species $j$.

In the CO$_2$ corrosion system, an anodic electrochemical reaction results in iron dissolution, shown as follows:

$$\text{Fe}(s) \rightarrow \text{Fe}^{2+} + 2e^-, \quad (5)$$

The following expression indicates its reaction kinetics [28]:

$$i_{\text{Fe}} = i_{0,\text{Fe}} 10^{\frac{\psi_i - \psi_{\text{rev,Fe}}}{\delta_{\text{Fe}}}}, \quad (6)$$

where $i_{\text{Fe}}$ (A·m$^{-2}$) and $i_{0,\text{Fe}}$ (A·m$^{-2}$) are current density of dissolution and exchange current density, and $b_{\text{Fe}}$ (mV/dec), $\psi_s$ (mV), $\psi_l$ (mV) and $E_{\text{rev}}$ (mV) are the Tafel slope of Fe, corrosion potential, potential in the solution and reversible potential, respectively. The formulation of exchange current density $i_{0,\text{Fe}}$ is [28]:

$$i_{0,\text{Fe}} = i_{\text{ref,Fe}} \cdot \left( \frac{c_{\text{H}^+}}{c_{\text{H}^+ \text{ref,Fe}}} \right)^{a_{1,\text{Fe}}} \cdot \left( \frac{c_{\text{CO}_2}}{c_{\text{CO}_2 \text{ref,Fe}}} \right)^{a_{2,\text{Fe}}} \cdot e^{-\frac{\Delta H}{RT} \left( \frac{1}{T} - \frac{1}{T_{\text{ref,Fe}}} \right)}, \quad (7)$$

where $\Delta H$ (kJ·mol$^{-1}$), $T_{\text{ref},j}$ (°C) are activation energy and the reference temperature, respectively. The surface concentration of CO$_2$ and H$^+$ can be solved by a mass transfer model, and all the other parameters are available in the work of [28].

According to Nešić et al. [33], cathodic electrochemical reactions mainly consist of hydrogen ion reduction and the direct reduction of carbonic acid:

$$2\text{H}^+(\text{aq}) + 2e^- \rightarrow \text{H}_2(\text{g}), \quad (8)$$

$$2\text{H}_2\text{CO}_3(\text{aq}) + 2e^- \rightarrow 2\text{HCO}_3^{-} (\text{aq}) + \text{H}_2(\text{g}), \quad (9)$$

Reaction kinetics of these can be expressed as [28]:

$$i_{\text{H}^+} = i_{0,\text{H}^+} 10^{\frac{\psi_i - \psi_{\text{rev,H}^+}}{\delta_{\text{H}^+}}}, \quad (10)$$

$$i_{\text{H}_2\text{CO}_3} = i_{0,\text{H}_2\text{CO}_3} 10^{\frac{\psi_i - \psi_{\text{rev,H}_2\text{CO}_3}}{\delta_{\text{H}_2\text{CO}_3}}}, \quad (11)$$

The exchange current density in the equations above are available in [28] and are listed as follows:

$$i_{0,\text{H}^+} = i_{\text{rev,H}^+} \cdot \left( \frac{c_{\text{H}^+}}{c_{\text{H}^+ \text{rev}}} \right)^{a_{1,\text{H}^+}} \cdot e^{-\frac{\Delta H}{RT} \left( \frac{1}{T} - \frac{1}{T_{\text{rev,H}^+}} \right)}, \quad (12)$$

$$i_{0,\text{H}_2\text{CO}_3} = i_{\text{rev,H}_2\text{CO}_3} \cdot \left( \frac{c_{\text{H}^+}}{c_{\text{H}^+ \text{rev}}} \right)^{a_{1,\text{H}_2\text{CO}_3}} \cdot \left( \frac{c_{\text{H}_2\text{CO}_3}}{c_{\text{H}_2\text{CO}_3 \text{rev}}} \right)^{a_{2,\text{H}_2\text{CO}_3}} \cdot e^{-\frac{\Delta H}{RT} \left( \frac{1}{T} - \frac{1}{T_{\text{rev,H}_2\text{CO}_3}} \right)}, \quad (13)$$

where standard hydrogen electrodes are used for the purposes of the equation.

2.2. Three-Dimensional CFD Method

The low-pressure part of a supercritical H$_2$O/CO$_2$ steam turbine with nine stages was designed by Zhang et al. [29] and is investigated in this study. The design parameters of the turbine are shown in Table 3. Three-dimensional CFD simulations were carried out using
the commercial software NUMECA. To reduce computational costs, the periodic boundary technique was adopted to model a single-blade passage for each blade row. The Autogrid module was utilized to generate the structured mesh. Subsequently, Reynolds-averaged Navier–Stokes (RANS) equations were solved and the Spalart–Allmaras turbulence model was employed. Total pressure and total temperature were imposed as the inlet boundary conditions, while the static pressure boundary condition was set at a radial position at the outlet and the simple radial equilibrium equation was applied. All solid walls were adiabatic and non-slip. A property table with a size of 300 × 300 was generated by assuming that the property parameters of H$_2$O/CO$_2$ were functions of the static pressure ($P_s$) and entropy ($s$) which ensured good accuracy and a high calculation speed. Figure 3 illustrates the dependence of total-to-static efficiency ($\eta_{ts}$) and the mass flow rate ($q_m$) on the number of nodes ($N_{\text{grid}}$). After checking the figures, the grid with $N_{\text{grid}}$ (being about 21 million) was taken for simulations of the supercritical H$_2$O/CO$_2$ turbine. The accuracy of the same CFD method was validated by [29].

Table 3. Design parameters of the investigated turbine.

| Parameter                | Unit | Value |
|--------------------------|------|-------|
| Mass fraction of H$_2$O | -    | 0.88  |
| Mass fraction of CO$_2$ | -    | 0.12  |
| Inlet total temperature  | K    | 888.15|
| Inlet total pressure     | kPa  | 5500  |
| Outlet static pressure   | kPa  | 16    |
| Mass flow rate           | Kg/s | 60.46 |
| Rotor rotation speed     | rpm  | 3000  |

Figure 3. Mesh independence analysis for the investigated turbine.

The surface roughness of the turbine blades increased gradually with the corrosion process on the blade surfaces. Wall function was used to describe the roughness of the turbine blades under different corrosion progressions. The equivalent sand roughness ($k_s$) was used to consider the effect of corrosion on working fluids [30]. The parameter $k_s$ was estimated by an empirical formula proposed by Adams et al. [34]:

$$k_s = 5.863R_a,$$

where $R_a$ is the profile arithmetic average deviation roughness. In this study, $R_a$ was obtained from the corrosion model.
3. Results and Discussion

3.1. Model Validation

To validate the accuracy of the CO$_2$ corrosion model developed in this study, the corrosion rate predictions were compared against the experimental results of de Waard [35] as shown in Table 4. The maximum prediction value was less than 10%, reflecting that the model meets the accuracy requirement.

| Temperature (°C) | Partial Pressure of CO$_2$ (bar) | Numerical Results (mm/y) | Experimental Results (mm/y) | Error (%) |
|------------------|----------------------------------|--------------------------|----------------------------|-----------|
| 30               | 1                                | 1.421                    | 1.3                        | 9.31      |
| 40               | 0.92                             | 1.560                    | 1.7                        | 0.02      |
| 50               | 0.88                             | 2.164                    | 2.3                        | −1.03     |
| 60               | 0.80                             | 3.793                    | 3.9                        | −4.85     |
| 70               | 0.69                             | 4.292                    | 4.3                        | 0.39      |
| 80               | 0.53                             | 5.197                    | 5.7                        | −8.82     |

3.2. Prediction and Analysis of CO$_2$ Corrosion

3.2.1. Results of CFD Simulation

Figures 4–6 show the pressure, temperature and dryness fractions on the surfaces of the blades, and the calculation of CO$_2$ corrosion rates was carried out with these parameters. It should be noted that the condensed water started to appear at the trailing edge of the 8th stage rotor. Therefore, the parameters of the fluid domain after the 8th stage stator were acquired, including pressure, temperature of condensed water, flow rate and dryness fraction, etc., and used to predict the corrosion rate with the corrosion model.

![Static Pressure (Pa)](attachment)

Figure 4. Static pressure distribution on the blade surface.
Figure 4. Static pressure distribution on the blade surface.

Figure 5. Static temperature distribution on the blade surface.

Figure 6. Dryness fraction distribution on the blade surface.

3.2.2. Corrosion Characteristics in the Initial Condensation Zone

Figure 7 illustrates the corrosion rate distribution on the blades of the last two stages, where the S8P represents the pressure surface of the 8th stage stator, R9S represents the suction surface of the 9th stage rotor and so on. Firstly, the temperature and pressure of the working fluid decreased gradually with the flow and some of the steam condensed into droplets. In Equation (3) and Table 2, the temperature decreased and this reduced the equilibrium constants of each chemical reaction, weakening the ionization of the $\text{H}_2\text{O}$ and $\text{CO}_2$ while strengthening the reverse reactions of each equilibrium reaction. Thus, the concentration of $\text{H}^+$ decreased and the reaction rate fell. With a decrease in pressure, the partial pressure of the $\text{CO}_2$ decreased and dissolution of the $\text{CO}_2$ was reduced. Hence, the concentration of $\text{H}_2\text{CO}_3$ decreased and the pH increased. Under the synthetic effect of temperature and pressure, according to Equations (7), (12) and (13), the current density of the electrochemical reactions decreased. Therefore, the corrosion rate in the ICZ of the turbine decreased stage by stage in general. Similarly, in one stage, the corrosion rate of the stator blades was larger than that of the rotor blades due to the decrease of temperature and pressure. Moreover, fluid was at a stagnation state at the leading edge of the blade and the temperature and pressure of the working fluid decreased with the flow in the blade flow path. Accordingly, the corrosion rate at the leading edge of the blade was larger than at other positions of the blade. For a single blade, the pressure and temperature
were higher at the pressure surface than at the suction surface. Thus, the pressure surface corroded more easily, while the corrosion rate at the suction surface was relatively small. Additionally, the blade did not suffer from corrosion near the trailing edge of the suction surface due to flow separation.

Figure 7 illustrates the corrosion rate distribution on the blade surfaces of the last two stages, year 0.

Figure 8 shows the average corrosion rate at different blade heights. Above 70% of the blade height on the 8th rotor, the dryness fraction was equal to 1, and the turbine blade was not corroded. At various blade heights, the loading of the blade was different so the reduction of temperature and pressure were diverse. For the rotor blade, the corrosion rate increased with the blade height and reached a maximum near the tip of the blade due to the pressure and temperature distribution caused by the secondary flow. Meanwhile, for the stator blade, the corrosion rate basically decreased with the blade height but increased near the tip due to the temperature rise caused by the flow loss.

Figure 8. Average corrosion rate at different blade heights.
3.3. Influences of \( \text{CO}_2 \) Corrosion on Turbine Blades

3.3.1. Influence on Turbine Performance

The tendency of performance decline of the overall turbine and the last two stages is shown in Figure 9. The total-to-static efficiency \( \eta_{ts} \) of the turbine decreased about 0.6% in the 10th service year, while that of the 8th and 9th stages was 1.5% and 5.1% at the same time, respectively. Figure 10 shows the relative Mach number at the 50% span of the 8th rotor when the service time is year 0, year 5 and year 10 (assumed to be the lifetime of turbine blades). With the increased roughness on the blade surfaces, the high Mach number zone gradually shrank. Meanwhile, the low velocity region extended with the increase of roughness, especially near the trailing edge of the suction surface. This indicates that the roughness of the blade surface decreases the velocity of near-wall fluids and thickens the boundary layer. The effect of turbulent viscosity caused by roughness decreases the potential energy of the working fluid, and the extension of the low velocity region results in a more intense wake flow, thus enlarging flow loss. After the 5th year, the effect of roughness was no longer significant, so the performance of the turbine became stable.

![Figure 9](image9.png) **Figure 9.** Tendency of performance decline.

![Figure 10](image10.png) **Figure 10.** Relative Mach number at 50% span of the 8th rotor in (a) year 0; (b) year 5; (c) year 10.
3.3.2. Influence on Corrosion Characteristics

Figure 11 shows the corrosion rate distribution on the blade surfaces of the last two stages at the 5th and 10th year. Compared with Figure 6, the corrosion area shrank with the service time and the condensation of steam was delayed due to the decrease in efficiency of the heat-power conversion. The initial condensation zone moved rearward and wetness decreased. The 8th rotor blade was the first blade with condensed water on its surfaces so the effect of the initial condensation zone movement was the most significant. Figure 12 shows the average static temperature, static pressure, dryness fraction and corrosion rate of the last two stages at different service times. Due to the rearward movement of the ICZ, the temperature, pressure and dryness fractions increased with time at each stage. However, with the increase of the dryness fraction, the region without condensed water extended, that is, the shrink of the corrosion area as mentioned above. The shrink of the corrosion area was particularly significant on the 8th rotor blade, as shown in Figures 6 and 11. Therefore, the average corrosion rate of the 8th rotor blade decreased significantly with the service time. Meanwhile, the blades of the 9th stage basically maintained a constant corrosion rate.

Figure 11. Corrosion rate distribution on the blade surfaces of the last two stages in (a) year 5; (b) year 10.
4. Conclusions

Supercritical H$_2$O/CO$_2$ turbines are critical equipment needed to accomplish efficient heat-power conversion in the cycle of coal gasification in supercritical water, so it is of great significance to ensure their safety and reliability. In this study, a method for predicting CO$_2$ corrosion in the ICZ of a 9-stage H$_2$O/CO$_2$ turbine was constructed and flow domain calculations of the turbine were adopted to analyze the corrosion behavior of the turbine blades. The corrosion results obtained can be used as data sources for a risk-based inspection (RBI) analysis. The main conclusions are:

1. In H$_2$O/CO$_2$ turbines, the temperature and pressure of the working fluid are the main factors affecting the CO$_2$ corrosion rate. In simple terms, the corrosion rate decreases with the temperature and pressure in the ICZ. For rotor blades, the corrosion rate increases with blade height and is larger near the hub (or the shroud for a stator blade). The most readily corrodlible position is the leading edge and the pressure surface at 60% height of the 8th rotor blade.

2. For 10 years’ service time with corrosion, the total-to-static efficiency ($\eta_{ts}$) of the turbine decreases about 0.6%, while that of the 8th and 9th stages decrease 1.5% and 5.1%, respectively. After the 5th year, the decline in performance is no longer significant. The
principle of this phenomenon needs more in-depth studies and investigations in order to be defined.

3. The corrosion area on the blade surfaces shrinks with the service time due to the rearward movement of the initial condensation zone. The corrosion rate of the first blade in the condensation zone decreases with the service time, while the corrosion rate of the other blades maintains a steady value.

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