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Determination of safe operation zone for an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system

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Abstract

This paper proposes a novel approach to determine the safe zone for an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system. The approach first ensures the compressor safety and then determines the overall system safe zone by analyzing the unsafe characteristics of main components. Safe performance of the hybrid system fueled with biomass gas at all operations is analyzed. Finally, the map of safe zone is obtained to avoid component malfunctions and system performance deterioration. Results show that the hybrid system can achieve a high efficiency 60.78%, which is an interesting reference for distributed power stations. Under all operations, two unbalanced energy zones exist, which may cause the short supply of O₂ or fuel for electrochemical reaction. The lower the rotational speed, the narrower the zone of carbon deposition takes place in the reformer or turbine inoperation caused by too low inlet temperature. However, the phenomenon of fuel cell thermal cracking due to over-temperature will be exacerbated. System layout also affects component safety especially for the fuel cell. In the safe zone, the system has a characteristic of high efficiency

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and low load with low rotational speed, vice versa. In other words, the powers and load adjustment ranges both decrease with decreasing rotational speed whereas the efficiency increases, which peaks at 63.43%.

Keywords: Intermediate temperature solid oxide fuel cell; Gas turbine; Hybrid system; Gasified biomass gas; Safe operation zone ; Safety measure

1. Introduction

The commercialized size of solid oxide fuel cell/gas turbine (SOFC/GT) hybrid systems can reach up to 100 kW to 10 MW when proper technologies are in place [1–3]. The systems are suitable for mobile applications and distributed power generation because they can function in a standalone manner to provide power [1,4]. More importantly, SOFC/GT hybrid systems are thought to be the most attractive energy conversion systems in future energy market because of high efficiency, low pollution, and fuel flexibility [5,6].

At present, studies on hybrid systems fueled with biomass gas mainly focus on system modeling [7,8], integration and optimization design [9–11], biomass fuel effect [12,13], and component parameter selection [14]. These studies have provided a fundamental basis for the successful application of biomass gas in hybrid systems. However, a large number of studies have showed that hybrid systems may suffer from many safety constraints in the operations of load variation or partial load scenarios because of high nonlinear multivariable and strong coupling [14–18]. These constraints can be classified into two categories: 1) from the matching and coupling characteristics between components [14,17,18] and 2) from the security of components themselves [15,16,18]. The instability phenomenon of compressor surge or choke

might appear because of too low or too high air when operation points deviate from the designed point. Severe instability can result in blade fracture [19–21]. Hence, border lines of surge or choke on characteristic maps are usually employed to distinguish working zones from instability zones [19,20]. Too high turbine inlet temperature (TIT) is caused by too high fuel–air ratio [21], potentially leading to the deformation of a turbine blade and even compressor surge [16,17]. Too low TIT will cause gas turbines to be inoperable. Fuel cell performance deterioration is mainly due to thermal cracking caused by too high SOFC working temperature (T_{SOFC}) or internal misdistribution of temperature and stress. It is closely related to structure, geometry dimension, material, and manufacturing technologies [23,24]. When thermal cracking occurs, electrochemical reactions do not process well, potentially leading to gas leakage or serious accidents [22,23]. For internal reforming fuel cell or single reformer, CH_4 and CO cracking reactions may be accompanied by CH_4 reforming reaction, leading to carbon deposition. It can plug gas diffusion pores and weaken the activated catalyst, causing the performance of cell or reformer to deteriorate [25,26]. Therefore, these phenomena must be avoided to ensure the safety operation of hybrid systems.

The part-load performance of hybrid systems considering partial safety factors has been studied by some researchers [27–34]. Kimijima et al. [27] evaluated the part-load performance of a 30 kW hybrid system. Without compressor surge, system efficiency can be maintained over 60% in the power range of 50%–100% under variable speed but too high turbine outlet temperature (TOT) will cause problems. Stiller et al. [28,29] analyzed the phenomenon of fuel cell thermal cracking at various operations caused by too high temperature, carbon deposition

in the anode, and oxygen backflow. The degradation and malfunction of the system were simulated at a load range of 53%–100%. Results show that a constant SOFC temperature can ensure the system to have a wide load range, but the operation is unstable and some feedback measures are required. By maintaining a constant SOFC temperature and TIT, Calise et al. [30] investigated the hybrid system performance at variable load operations by changing air flow, fuel flow, and by-pass valves before the combustor and turbine. Milewski et al. [31] studied the part-load performance of a hybrid system with the constraints of T_{SOFC} , TIT, and surge margin (SM), which provided safe operational zones for partial rotational speed (RS) (0.9, 1, 1.05).

Stamatis et al. [32] designed a hybrid system with exergy efficiency of 59.8% at design point and controlled variable speed to increase system efficiency. Barelli et al. [33] investigated the part-load performance of an SOFC/GT hybrid system by changing RS with outlet temperatures of the fuel cell, reformer, and heat exchanger (HE) constant. However, the effects of safe factors in previous studies [32,33] were not considered. Komatsu et al. [34] investigated the effect of variable speed on system performance under a certain SM. They analyzed the variation trends of the temperature gradient (TG) in a fuel cell and reformer and showed that the fuel cell TG increases at low load operation.

All aforementioned studies on the part-load performance of hybrid systems are based on natural gas, and they maintain fuel cell temperature or TIT constant to study the safe performance by changing air flow, fuel flow, and current density. However, it is difficult to keep operation parameters constant in real operation because of control complexity and high design costs. Additionally, given the lack of an independent air supply system and thermal

management module, variable speed operations of a gas turbine (GT) will cause security issues for other components. For example, the increase in RS will cause the performance degradation of fuel cells, the reduction in RS will cause compressor surge, and quicker responses of GT on load variations than that of the fuel cell may trigger internal temperature maldistribution in the fuel cell [22]. In order to generate the same power, the fuel flow of biomass gas should be higher than that of natural gas because of its relatively lower heating value. Due to the flow characteristics of a turbine, large fuel flow will make the operation point to deviate from the design point, consequently causing compressor surge [35]. However, the solution by purely changing RS to reduce air flow will cause the GT to work at a low-speed zone, leading to decreased load. Most existing research on part-load operations of the hybrid system only considered partial safety factors but did not deeply discuss and determine the safe operation zones.

Hence, the safe operational zones of hybrid systems under various operations have to be determined in order not only to provide knowledge on system safety for designers and users, but also help take safety measures to avoid component damage or system performance deterioration. Such knowledge can also benefit system layout, component parameter selection, and optimization design.

In this work, the mathematical model of an intermediate-temperature solid oxide fuel cell and gas turbine (IT-SOFC/GT) hybrid system fueled by biomass gas is established. The safe operating characteristics of the system at all operations are analyzed. Six safe factors, such as compressor surge and choke, turbine inlet temperature, fuel cell working temperature, etc. are

considered to determine the safe operation zone. Ultimately, the map of safety operational zone is obtained for designing safety measures to avoid components malfunctions and system performance deterioration. Thereafter, the controllable parameter ranges and advantageous operation zones are derived.

2. IT-SOFC/GT mathematical model

2.1 IT-SOFC/GT hybrid system structure

A schematic layout of the IT-SOFC/GT hybrid system is shown in Fig. 1, which mainly includes IT-SOFC, single-shaft GT, external reformer, catalytic combustor (CC), fuel compressor, water syringe pump, generator, and other components. To avoid carbon deposition, water is added for maintaining the ratio of steam to carbon [31,36] by adjusting valve 1. To prevent seal and vibration caused by the pressure difference between the anode and cathode in the fuel cell [30], biomass gas needs to be compressed by a fuel compressor before entering the fuel cell for electrochemical reaction, which is adjusted by valve 2. The air flow is controlled by GT adjustment system and the RS of GT is controlled by generator equipment. Air pressurized by the compressor is heated by HE 1 and 2, which then enters the SOFC cathode to provide O₂ for electrochemical reaction. Water is first heated in the evaporator to be converted into steam and then mixed with biomass gas in the mixer. The mixed gas enters the reformer after being heated by HE 1. Reformed gas enters the fuel cell anode to provide H₂. The unreacted fuel from the SOFC anode will be completely combusted in the CC. High-temperature gas enters the turbine to generate power after heating air. The exhaust gas of the turbine preheats fuel and air, and then heats the evaporator before being released into the

atmosphere.

2.2 IT-SOFC/GT hybrid system modeling

2.2.1 IT-SOFC

This work uses the model of anode-supported IT-SOFC (873–1,073 K) developed by Aguiar [23], with the consideration of strict requirements of high-temperature solid oxide fuel cells (1,073–1,273 K) for material and sealing. We have previously studied the detailed mathematical model of IT-SOFC fitted into a hybrid system [24]. All important equations of this model are shown in appendix A. Fuel cell geometric parameters, physical parameters, and operating conditions can be easily found in the literature [23,24].

The SOFC stack is assumed to have 912 planar fuel cells, providing 144 kW power. The T_{SOFC} , average current density, and fuel utilization are chosen to be 1,073 K, 5,000 A/m², and 75%, respectively. The temperature of channels of fuel, air, and PEN structure at the design point along with fuel cell length is shown in Fig. 2 (a). The temperature profiles first decrease and then increase gradually, finally peaking at the exit. The current density, voltage, and various potential losses at the design point along with fuel cell length are shown in Fig. 2 (b). Results show that various potential losses gradually decrease and the cathode and anode polarization losses are dominant, followed by ohm loss and concentration loss. These variation trends are consistent with those in literature [23,36].

2.2.2 Gas turbine

To satisfy the flow match between a fuel cell and GT, the structure and aerodynamic

parameters of GT are determined, which mainly include a centrifugal compressor and radial turbine. The basic parameters of the compressor (such as geometrical shape, size, and speed) determine not only the flow characteristics of gas in the impeller, but also the relationship between flow rate, pressure, and RS [19–21]. The structure and aerodynamic parameters of the compressor and turbine are calculated and determined based on the GT design method [19]. For an impeller wheel with a diameter of about 200 mm, the speed should not exceed 45,000 r/min with a margin of 10% [37]. Hence, in this study, the RS of GT is set to 35,000 r/min. The compressor pressure and turbine expansion ratios are 3.2 and 3.0, respectively, considering component pressure losses. The TIT is 1173 K and the design flow rate of the turbine is 0.27 kg/s. The initial parameters and main structural parameters are shown in Table 1 and other detailed information can be found in [24,37].

According to these structural parameters, a previous study [37] has designed 3D blades and simulated the internal flow in compressor and turbine using impeller design software of Concept NREC. The simulation results were compared with the GT experiment data from Jiangjin Turbocharger Plant, China. The compressor efficiency is 70%–84%, and turbine efficiency is greater than 80% with a maximum close to 83%. Thus, the aerodynamic design of GT is reasonable.

Characteristics maps are generally used to represent the operation performance of GT at different conditions. In order to capture generality, the reduced parameters of air flow rate, pressure ratio, efficiency, and RS are introduced [21]. This study uses the similar principles to scale and fit the existing gas turbine maps [38, 39] and obtains the characteristic maps that meet

design requirements, as shown in Figs. 2 (c) and (b). The mathematic model of GT is shown in appendix A.

Given that each speed curve in the compressor characteristic map corresponds to a wide range of mass flow rate and pressure ratio, when operation condition changes the two parameters under different speed curves can overlap. Thus, the relationship between mass flow rate and pressure ratio must be established in order to determine a unique operating status. As shown in Fig. 2(c), β lines are used as an auxiliary coordinate to determine operating status. The β line, obtained by a second-order polynomial, is used to determine mass flow rate, pressure ratio, and efficiency [24,34].

2.2.3 Reformer

In this work, the wood chip gasified gas composed of 4.53% CH₄, 23.64% H₂, 13.87% CO, 17.92% CO₂ and 40.04% N₂ is chosen as fuel. The composition is obtained through a two-stage gasification experiment developed by the Institute of Thermal Engineering at Shanghai Jiao Tong University [40]. Gasified gas should be reformed before entering fuel cells, where the reforming model is shown in appendix A. It is established according to Gibbs free energy thermodynamic equilibrium reaction, mainly including strong endothermic steam reforming reaction (1) and weak exothermic water gas shift reaction (2). Six type flows of CH₄, H₂, CO, CO₂, H₂O, and N₂ in the reforming model can be calculated by the equilibrium Eqs. (3) and (4). The amount of H₂ flow entering SOFC can be calculated by Eq. (5).





$$K_1 = \frac{[\text{CO}][\text{H}_2]^3}{[\text{CH}_4][\text{H}_2\text{O}]} = \frac{(n_{\text{CO}} + x - y)(n_{\text{H}_2} + 3x + y)^3}{(n_{\text{CH}_4} - x)(n_{\text{H}_2\text{O}} - x - y)(n_t + 2x)^2} \quad (3)$$

$$K_2 = \frac{[\text{CO}_2][\text{H}_2]}{[\text{CO}][\text{H}_2\text{O}]} = \frac{(n_{\text{CO}_2} + y)(n_{\text{H}_2} + 3x + y)}{(n_{\text{CO}} + x - y)(n_{\text{H}_2\text{O}} - x - y)} \quad (4)$$

$$n_{\text{H}_2, \text{tot}} = n_{\text{H}_2, \text{in}} + n_{\text{CO}, \text{eq}} + 3n_{\text{CH}_4, \text{eq}} \quad (5)$$

The reforming characteristics and composition in the equilibrium system with temperature are shown in Figs. 2 (e) and (f). As reaction temperature rises, K_1 increases sharply and K_2 decreases gradually. H_2 flow reaches the maximum value at 890 K, whereas H_2O flow reaches the minimum value of 873 K.

2.2.4 Other components

The hybrid system also includes other components, such as CC, HE, mixer, and syringe pump. These models and their parameters can be found in [38,39]. This work assumes that unreacted fuel is completely combusted in the CC.

The hybrid system electric efficiency is defined as:

$$\eta_{\text{HS}} = \frac{P_{\text{SOFC}} \cdot \eta_{\text{DC/AC}} + (P_T - P_{\text{C,air}}) \eta_g \cdot \eta_m - (P_{\text{C,fuel}} / \eta_e) - (P_{\text{P,water}} / \eta_e)}{(y_{\text{CH}_4}^0 \cdot \text{LHV}_{\text{H}_2}^0 + y_{\text{H}_2}^0 \cdot \text{LHV}_{\text{H}_2}^0 + y_{\text{CO}}^0 \cdot \text{LHV}_{\text{CO}}^0) \cdot M_{\text{fuel}}} \quad (6)$$

2.3 Hybrid system design parameter and operation constraint

The presented work designing the hybrid system is based on the matching between the experiment data of micro gas turbine [37] and physical features of fuel cell [23,24]. The design parameters of the hybrid system are shown in Table 2. In this study, the fuel compressor has a pressure ratio of 3.2 and efficiency of 80%, which are equal to those of the air compressor.

For fuel cell operation, the appropriate operating temperature range can not only guarantee structural stability but also make the fuel cell have good performance. The temperature gradients of fuel cell mainly depend on the properties of materials, operating conditions, and design. Larger temperature gradients can cause excessive stresses within the SOFC components and even lead to cell breakdown [41]. Thus, for fuel cell safety, the T_{SOFC} should be within the allowable temperature ranges of materials, and the fuel cell mean temperature gradient (MTG) should be below the maximum allowable local temperature gradient 10 K/cm [23,41].

For compressor operation, surge boundary is very important because a compressor easily enters surge state by increasing π at a constant flow rate or decreasing flow rate at a constant π . In this case, the airflow in the compressor can yield intense pulsation and produce reverse flow, which can cause the blade to vibrate and even break [20,21]. Therefore, the compressor should be operated away from the surge line, where an SM can be used to evaluate the distance from working point to surge boundary. The computational formula of SM can be found in [24] and this paper sets the lower limit value of SM to 12% during off-design condition [21].

Choking is another unstable phenomenon in compressor operation. Compressor performance deteriorates sharply if operated under a certain speed when air flow is increased to a certain value. In this case, the airflow or exhaust pressure cannot be increased [20,21]. Compressor choking flow can be determined by either experiment or calculation, where the latter is selected in this work. In the calculation, choking flow can be calculated in the critical flow states of through-flow components. For a centrifugal compressor, the choking phenomenon often occurs in inducer inlet throat or vaned diffuser inlet throat [20]. Based on

above structural parameters of the gas turbine, the choking flow is calculated as 0.2 kg/s at the design point by using the following formulae.

The choking flow in the inducer inlet throat is:

$$m_{cr} = c_{ci} A_{ci} \rho_1^* a_1^* \left\{ [2 + (k-1)(u_c^2 - 2u_1 c_{1u}) / (a_1^*)^2] / (k+1) \right\}^{\frac{k+1}{2(k-1)}} \quad (7)$$

The choking flow in the vaned diffuser inlet throat is:

$$m_{cr} = c_{rd} A_{cd} \rho_2^* a_2^* [2 / (k+1)]^{\frac{k+1}{2(k-1)}} \quad (8)$$

The TIT is also constrained by blade material and cooling technologies, as too high TIT can damage the blade, whereas too low TIT can affect GT operation [21,38,39].

In reforming process, the S/C ratio (the ratio of steam to CH₄, CO, and CO₂) is an important parameter for avoiding carbon deposition [31]. The boundary value of the S/C ratio (S/C_{bv}) is dependent on the reaction temperature [36], as shown in Eq. (9). When it is less than the setting value, carbon deposition can be avoided effectively. In this study, the setting value of S/C is 2. The S/C_{bv} is calculated based on real reaction conditions in the reformer. When S/C_{bv} is less than 2, no carbon deposition occurs [31].

$$S / C_{bv} = [A_{s/c} \tanh(C_{s/c} \bullet (T - 273.15) + D_{s/c}) + 1] / 2 + B_{s/c} \quad (9)$$

Specific constraints on parameters are summarized in Table 3.

2.4 IT-SOFC/GT hybrid system calculation

U_f is important for component safety: i) too low U_f leads to turbine over-temperature, compressor surge, and carbon deposition; ii) too high U_f leads to the steep internal temperature gradient in fuel cell and thermal cracking [41]. Hence, in various operations in this study, U_f is

fixed at 75%. The dimensionless values for fuel flow change between 10% and 130% of the design value and rotational speed change is 60%–110% of the rated value. The corresponding airflow and pressure ratio change in relation to characteristic curves.

Considering the thermal coupling and safety constraints among components, a reasonable and scientific calculation flowchart is an important prerequisite for analyzing the operation performance of the hybrid system and determining its safety operational zones. The specific calculation flowchart of IT-SOFC/GT is shown in Fig. 3.

The proposed hybrid system mainly uses the following three functional models to calculate and distinguish system circulation features: 1) thermodynamic parameter calculation and component matching, 2) determination of component safety performance, and 3) iteration cycle and matching of the whole system. The hybrid system performance is simulated by using a mathematical model in MATLAB/SIMULINK. The reforming equilibrium reactions are solved using MATLAB programming, and component judgment modules are realized by user-defined functions. Each calculation cycle for a working condition needs 1572 iterations to converge and overall, approximately 5,659,200 calculations are necessary to establish all variation conditions in this work.

There are also some assumptions for reducing the complexity of calculation cycle. 1) In the SOFC, only H_2 participates in the electrochemical reaction, and the electrochemical reaction of CO is not considered. 2) The hybrid system has zero leakage, and the output temperatures of the fuel cell and reformer are their reaction temperatures. 3) Heat and pressure losses of components are constant in operation conditions. 4) The operating voltage of each fuel

cell is constant.

3. Performance analysis of IT-SOFC/GT at design condition

The values at each node and operation performance at design condition are obtained by using above established IT-SOFC/GT mathematic models, as shown in Tables 4 and 5.

Table 4 shows that the reformer outlet temperature (node 13) is 810 K, with K_1 and K_2 of 0.04 and 3.82 respectively (can be found in Fig. 2(e)). In this case, CH_4 and CO are not completely reacted, with residual amounts of 0.10% and 5.52% respectively. However, H_2 increases to 24.76% due to the combination from the reforming reactions of CH_4 and CO . T_{SOFC} (node 14) is 1,073 K, and MTG is 6.58 K/cm, both meeting the safety constraints in Table 3. Given the electrochemical reaction, H_2 decreases from 24.76% to 1.80%. The unreacted fuels (H_2 , CH_4 , and CO) from SOFC anode are completely converted into H_2O and CO_2 in the CC to improve the thermodynamic performance of the overall system. Furthermore, the combusted gas guarantees that the TIT is 1,173K after preheating the air entering the fuel cell cathode. Turbine expanding ratio is about 3 due to the pressure losses from components, and all of which meet the GT design requirements (see Tables 2 and 3).

Table 5 shows that S/C_{bv} of 1.87 is less than 2, which can effectively prevent carbon deposition and the cell voltage matches with that in [23]. Other key performance parameters are also provided in Table 5. It is noted that for small power hybrid system designed in this work, the electrical efficiency is 60.78% and it agrees with that in [32]. This high efficiency indicates it is very suitable for being used in distributed power stations. However, biomass gas has considerable influence on compressor consumption power because of its low heating value.

4. Safe zone determination of IT-SOFC/GT.

4.1 Safe performance analysis of IT-SOFC/GT in all operations

In this study, the performance parameters change in real time that reflects the reality at various operations, without assuming parameters such as T_{SOFC} , TIT, or TOT to be constant.

For each operating status under RS, air flow and fuel flow are independent and each input pair can generate an operation point. The operation characteristic surface for each RS is obtained by connecting these points, as shown in Figs. 4–6.

On compressor characteristic maps, the airflow and pressure ratio under each RS do not monotonously increase or decrease in relation to changing operation points. Therefore, in order to determine the unique operation points, the coordinate system of β (0–1) and relative rotational speed (RRS) (0.6–1.1) are used to reflect the variations in compressor SM and choking flow, as shown in Fig. 4 (a). The left part represents the variation trend of surge margin with respect to RRS and β , and the right part represents the variation trend of air flow.

From left part in Fig.4(a), we can see that for a fixed rotational speed SM decreases from 51.32% at β of 0 to 0 at β of 1 when $n = 0.6$. For variable rotational speed, SM increases with increasing rotational speed. On the other hand, the right part in Fig.4(a) show that for a fixed rotational speed with rising β , air flow does not change at the initial stage and starts to decline, followed by a great reduction. However, the higher the rotational speed, the more obvious this trend is. Surge zone is defined as the surge margin lower than 12%, which is shown by the purple zone in Fig.4(a). Choking zone is defined as the air flow reaching its maximum and cannot be added anymore, which is shown by the blue zone in Fig.4(a). Therefore, in the surge

zone, air flow decreases and compressor pressure ratio increases (see Fig.2(c)), and consequently every operation point is away from the choking zone. On the contrary, in the choking zone, airflow increases and pressure ratio decreases (see Fig.2(c)), and thus operation points are far from surge area.

Figure.4(b) shows that the variation trend of TIT with different RS. Even if there are some overlaps between these trends, the variation trend for each RS can be clearly expressed. For a certain RS, TIT slowly increases and then rapidly increases with increasing fuel flow, which is illustrated by the transition from the blue low-temperature surface to the red high-temperature surface. With increasing air flow, TIT sharply decreases and then slowly decreases and two boundary lines appear on the TIT surface of each RS because of the setting of β . According to energy and mass balance equations among all components, TIT varies within the area defined by the minimum and maximum values of air. By using $n = 0.6$ as an example, when air flow is maximum ($\beta = 0$) TIT varies between 842 K and 1354 K, whereas TIT varies between 857 K and 1375 K for minimum air flow ($\beta = 1$). All TITs under this RS change are within the two arrays. Similarly, every TIT surface has two extreme operating points, defined as TIT_{\min} of 842 K and TIT_{\max} of 1375 K. It is worth noting that with the RRS decreasing from 1.1 to 0.6, the air flow gradually reduces and the increase in fuel flow can lead to a higher TIT. This situation makes the temperatures of many operating points exceed the upper limit requirements of turbine material. Even worse, it could cause the whole thermodynamic calculation system to halt because of the appearance of unbalanced energy among these components, particularly in low RRS(from 0.6 to 0.8) zones. This is why the TIT surface interfaces change in steps

between low RSs. Even so, the maximum TIT with low RS is higher than that of high RS. For example, TIT decreases from 1375K with RRS of 0.6 to 1262K with RRS of 1.1. In practice, some serious phenomenon will appear, such as turbine inlet material deformation or fuel cell performance degradation due to over-temperature. Thus, with increasing RS, the unsafe regime caused by too low or too high TIT shrinks, which helps widen GT operating range.

Carbon deposition area is defined as the S/C_{bv} of operation point greater than 2. Fig. 5 (a) shows that for a certain RS, S/C_{bv} in the reformer with increasing fuel flow shows a slight rapid decrease and followed by a slow decrease, which is illustrated by the transition from the red high S/C_{bv} surface to the blue low S/C_{bv} surface. With increasing air flow, S/C_{bv} increases gently. Carbon deposition zone increases with increasing RS, mainly because the air fuel ratio shrinks greatly when the system is operated at the condition of high RS and low fuel flow. Even worse, it can further lead to temperature decrease in reformer inner and increase in S/C_{bv} . This case means that the water added in the reformer is less than that is needed to avoid carbon deposition. Hence, if the system operates for a long period, the reformer exit might be blocked or catalyst activity is reduced. Fortunately, this dangerous phenomenon can be alleviated appropriately by adjusting water or fuel valve.

A fuel cell is the core component of the hybrid system, whose safety characteristics are vital to the whole system. Figure. 5 (b) shows that the T_{SOFC} surface variation trend is similar to that of TIT, but the increasing slope is different in a different range. For a constant rotational speed, T_{SOFC} sharply and then slowly increases with increasing fuel flow, while it decreases slowly with rising air flow. With rotational speed increasing, the variation range of T_{SOFC}

shrinks. Because the minimum T_{SOFC} increases from 854K with RRS of 0.6 to 915K with RRS of 1.1, the maximum T_{SOFC} decreases from 1267K to 1142K. Even interestingly, when fuel flow is low T_{SOFC} is higher than TIT, but with increasing fuel flow T_{SOFC} is lower than TIT. This phenomenon can be observed by comparing the temperatures of the fuel cell and turbine inlet at the same section. The main reason is that for too low fuel flow, the unreacted fuel after SOFC electrochemical reaction entering the combustor is very low, whereas the rise in combustor outlet temperature is not obvious. Thus, the gas temperature will decrease after passing HE, causing TIT to be lower than T_{SOFC} . With rising fuel flow, the combustor outlet gas temperature increases greatly. After passing HE, apart from adding heat to the SOFC, TIT initially increases and then becomes gradually higher than T_{SOFC} . Therefore, the parameter selection of HE is also important for system operation.

Figure. 5 (c) shows the variation trends of fuel cell MTG, which is another factor representing cell safety. For each rotational speed, the fuel cell MTG has a minimum. The reason is that for too low fuel flow, reformer temperature is very low and water gas shift reaction plays a major role and releases heat, causing the reformer outlet temperature to increase, but the temperature difference of both ends of the fuel cell to decrease. Finally, fuel cell MTG decreases. However, with increasing fuel flow, the reformer temperature increases and CH_4 reforming plays a major role and absorbs heat, causing the reformer outlet temperature to decrease. In this case, the temperature difference of both ends of the fuel cell, as well as fuel cell MTG, increases. This phenomenon indirectly shows that the fuel cell inner temperature profile changes sharply in variable load operations, which is a great challenge for the thermal

expansion of fuel cell materials. More important is that with decreasing RS, the fuel cell MTG exceeds the thermal expansion limit. It can be found that the maximum fuel cell MTG 10.23K/cm appears under the condition with the rotational speed of 0.6. This could result in thermal cracking. Obviously, system layout also affects the safe performances of components, particularly for the fuel cell.

Each pair of fuel flow and RS determines a certain power or efficiency of the hybrid system when the simulated running without alarming. The tendencies of system power and efficiency are shown in Figs. 6(a) and (b) respectively. For the same reason (mismatch between fuel flow and air flow), the power and efficiency surface interfaces changes in steps between low RSs.

As shown in Fig.6(a), at a constant rotational speed, the hybrid system output power increases with increasing fuel flow but the power first increases and then decreases gently with increasing air flow. However, at variable rotational speed, the minimum system power increases from 58.58kW with RRS of 0.6 to 138.7 kW with RRS of 1.1, and the maximum power also increases from 96.65kW to 242.97 kW. This results in the increase of load adjustment range. With increasing fuel flow, the system efficiency first increases sharply and then slowly, which is illustrated by the variation from the blue surface to the red surface in Fig. 6 (b). However, the minimum system efficiency decreases from 59.55% with RRS of 0.6 to 55.55% with RRS of 1.1, and the maximum value decreases from 64.43% to 62.30%. It is important to note that the various trends of power and efficiency reflect system operating characteristics in all conditions. The tendencies of power and efficiency in safe operations can

be obtained by removing the unsafe operating data in Section 4.2.

4.2 Safe zone determination of IT-SOFC/GT

To clearly determine safe operation zones of the hybrid system in all operations, this work first determines the safe operation zone of the compressor shown in Fig. 7 (a). In general, the wider the safe and stable operating range, the better the off-design performance of compressor is. Other safety factors are then analyzed, and the map of the safety operational zone is obtained in Fig. 7(b).

As shown in Fig. 7 (a), the compressor surge zone (depicted in purple) is confined by the SM (equaling to 12%) line and the surge boundary line. Experimental data shows that strong vibrations would happen to the compressor, and meanwhile turbine inlet temperature rises sharply and even exceeds the upper limit. Choking zone (depicted in blue) is formed by choking flow line and boundary line (lower right) on the characteristic map. In this zone, compressor consumes a large amount of power to overcome the increase of flow loss, but the air pressure cannot be improved, leading to a sharp deterioration in performance. Furthermore, TIT below the lower limit of working temperature may also be caused (see Fig.4(b)). The lower left zone represents the minimum speed limit zone, where compressor pressure ratio and air flow rate are very low. The enthalpy reduction passing the turbine almost equals to the compressor consumption power, which leads gas turbine to operate in a self-sustained state. The left zone is the compressor safety operational zone as shown in green in Fig. 7 (a).

For simplicity purpose, the dimensionless reduced air flow (RAF) (or RS) and relative fuel flow (RFF) are used to represent the operational range for the fuel cell, reformer, and turbine.

Fig.7(b) shows the component safe and unsafe zones as a function of RAF and RFF.

The yellow zone on the upper left (low air flow or RS and high fuel flow) represents a regime where system unbalanced energy state exists. Another unbalanced energy zone, caused by too much air flow (or too high RS) and low fuel flow, is depicted in yellow in the lower right. This situation can cause thermodynamics mismatch in components, which further leads to thermodynamic failure of the overall system. It is why at different speeds, the trends of characteristic parameter changes in steps when the fuel flow are too low or high, as shown in Figs.4(b), 5(b) and 6.

The gray zone presents that carbon is easy to deposit in the reformer. This is because lower fuel flow causes reformer working temperature to decrease. It is noted that there is a dark gray zone in the gray zone, where the TIT is too low. The gas turbine performance will decrease and is thus recommended to operate in this zone. That is because that too low fuel flow causes the turbine to cool down strongly and, therefore, the TIT is lower than the working requirement value. However, in order to avoid reformer or turbine malfunctions, a fuel valve before CC or heat compensation units would be needed, such as an electrical heater.

In the red zone (high fuel flow and low air flow), the fuel cell and turbine are heated sharply and, therefore, thermal cracking or turbine material defamation may occur on them. It is interesting to note that, with decreasing air flow (or RS), the component over-temperature zone decrease, but these temperatures increase (see Figs.4(b) and 5(b)). It is also found that, when RAF is lower than 0.85 (or RRS is lower than 0.9), the fuel cell begins to suffer from over-temperature (depicted in dark red). This also can be solved by adjusting gas turbine

rotational speed or fuel valve. Fig.7(b) also shows that the variation of each operational zone has a wave mode for each RS, resulting from gas turbine characteristics maps (Figs. 2(c) and (d)).

The safe operation zone of the hybrid system in all operations is shown in green in Fig. 7(b). In the safe zone, load change can be realized by combining air flow(or RS) and fuel flow. Another important result is that the system has an operating characteristic of high efficiency and low load in low RS (or air flow) zone, vice versa. With decreasing RRS, the minimum output power of the hybrid system decreases from 138.70 kW with RRS of 1.1 to 67.12 kW with RRS of 1.1, and the maximum power also decreases from 242.97 kW to 126.90 kW, which leads to the decrease in load adjustment range. The minimum efficiency increases from 55.55% to 59.55%, and the maximum efficiency is 63.43%. Hence, other compensatory methods should be taken if the safe zone needs to be widened.

An important result from the above analysis is also summarized in Fig.8. In order to ensure safe operation, the unsafe characteristics of some components (such as fuel cell, turbine, and reformer) mainly affected by temperature can be relieved by adjusting valves and operating modes. Other methods may also be advantageous by adding auxiliary components. However, unlike other components, the compressor mainly suffers from two complex events: surge and choke. These should be relieved in compressor structure design and operating condition. The information is helpful for designers or users in system design, selection of system configuration and the decision of operation modes. For example, in order to avoid compressor surge or choke, a designer can select appropriate parameters of structure and aerodynamic to expand the stable

zone to avoid the gas turbine unstable operation.

Although the quantitative results are only applicable to the hybrid system established in this work, the safety operation variation trends and designed method can benefit the design and operation of other similar practical hybrid systems. For safe operation of hybrid systems, our future work will investigate how to select preventive measures to avoid accidents and investigate their effects.

5. Conclusions

This paper has introduced a novel approach to determine the safe operation zones for an IT-SOFC/GT hybrid system fueled with biomass gas at all operations. Through simulations, the following key points are observed.

(1) The small power hybrid system 182kW designed in this work has a high electrical efficiency 60.78%, which is an interesting reference to the distributed power station.

(2) For all operations, two unbalanced energy zones exist, which cause O₂ or fuel in short supply for the electrochemical reaction. The lower the rotational speed, the narrower the zone of carbon deposition took place in the reformer or turbine inoperation caused by too low inlet temperature. However, the phenomenon of fuel cell thermal cracking due to over-temperature can be exacerbated. System layout also affects the safe performance of components, especially for the fuel cell. If the safe zone needs to be widened, other compensatory methods should be adopted.

(3) In safe operation zone, the system has the operating characteristics of high efficiency and low load in the low RS zone, vice versa. In other words, the power and load adjustment

ranges both decrease with decreasing RS, whereas the efficiency increases, peaking at 63.43%.

(4) To ensure system safety, the unsafe characteristics of components mainly affected by temperature can be relieved by adjusting valves or operating modes. However, compressor surge and choke should be relieved from compressor structure design and operating conditions. The information is helpful for designers or users in system design and selection of system configuration.

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8. Nomenclature

Nomenclature	
M	mole flow rate(kg s-1)
m_{cr}	choking flow in the inducer inlet throat(kg s-1)
c_{ci}	correction coefficient, 0.86~0.91
A_{ci}	inducer cross sectional area(mm ²)
ρ_1^*	air stagnation density at the exit of the submerged inlet (kg m-3)
a_1^*	air stagnation sound at the exit of the submerged inlet (kg s-1)
k	air adiabatic index
u_c	circumferential velocity at the exit of inducer external diameter(m s-1)
u_1	impeller convected velocity (m s-1)
c_{iu}	impeller inlet prewhirl (m s-1)
c_{rd}	correction coefficient, 0.82~0.0.90
A_{cd}	vaned diffuser inlet throat area(mm ²)
ρ_2^*	air stagnation density at the inlet of vaned diffuser(kg m-3)
a_{t2}^*	air stagnation sound at the inlet of vaned diffuser(kg s-1)
n_i	composition i mole flow rate(mol s-1)
K_1	CH ₄ reforming reaction equilibrium constant
K_2	water gas shift reaction equilibrium constant
LHV_i^0	lower heating value of composition i in a standard state (kJ mol-1)
S/C_{bv}	boundary value of the S/C ratio
$A_{S/C}$	constant for boundary value of the S/C ratio, -1.044
$B_{S/C}$	constant for boundary value of the S/C ratio, 1.369
$C_{S/C}$	constant for boundary value of the S/C ratio, 9.971×10^{-3}
$D_{S/C}$	constant for boundary value of the S/C ratio, -6.497
T	reformer working temperature
P_{SOFC}	SOFC output power(kW)
P_T	turbine output power(kW)
$P_{C,air}$	air compressor consumption power(kW)
$P_{C,fuel}$	fuel compressor consumption power(kW)
$P_{P,water}$	water syringe pump consumption power(kW)
$\eta_{DC/AC}$	DC/AC inverter efficiency (%)
η_g	electric generator(%)

η_m	GT mechanical efficiency (%)
η_e	electric motor efficiency(%)
y_i	composition i mole fraction(%)
x	CH ₄ consumption mole in reforming reaction
y	CO consumption mole in reforming reaction
Abbreviations	
IT-SOFC	intermediate-temperature solid oxide fuel cell
TIT	turbine inlet temperature
SM	surge margin
GT	gas turbine
PEN	Positive-electrode/solid Electrolyte/Negative -electrode
NREC	the northern research engineering company
RS	rotational speed
HE	heat exchanger
TG	temperature gradient
MTG	mean temperature gradient
CC	catalytic combustor
RRS	relative rotational speed
RAF	relative air flow
RFF	relative fuel flow
<i>tot</i>	total
<i>in</i>	inlet
<i>eq</i>	equilibrium

Figure Caption List:

Figure. 1 Schematic of IT-SOFC/GT hybrid system, C:compressor, T:turbine, HE: heat exchanger.

Figure. 2 Characteristic curve of components: (a) fuel cell temperature profiles, (b) current density, voltage and potential losses distributions, (c) compressor pressure ratio, (d) compressor efficiency, (e) K_1 , K_2 , S/C_{bv} with temperature, (f) composition with temperature.

Figure. 3 Circulation flowchat of IT-SOFC/GT.

Figure. 4 Safe performances of gas turbine: (a) compressor characteristic, (b) turbine inlet temperature,

Figure. 5 Safe performances of reformer and fuel cell: (a) boundary value of the S/C ratio, (b) IT-SOFC working temperature, (c) IT-SOFC mean temperature gradient.

Figure. 6 Variation trends of hybrid system performance: (a) hybrid system output power, (b) hybrid system efficiency.

Figure. 7 Map of the safe operation zone in all operations: (a) safe operation zone of compressor, (b) safe operation zone of hybrid system.

Figure. 8 Summary measures for the hybrid system safety.

Table Caption List:

Table. 1 Initial parameter and main structure parameter of GT.

Table. 2 IT-SOFC/GT hybrid system design parameter.

Table. 3 IT-SOFC/GT Hybrid system operation constraint.

Table. 4 IT-SOFC/GT hybrid system calculation value at each node.

Table. 5 IT-SOFC/GT hybrid system performance.