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Stall/surge dynamics of a multi-stage air compressor in response to a load transient of a hybrid solid oxide fuel cell-gas turbine system

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HIGHLIGHTS

- Dynamic operation of a hybrid solid oxide fuel cell gas turbine system was explored.
- Computational fluid dynamic simulations of a multi-stage compressor were accomplished.
- Stall/surge dynamics in response to a pressure perturbation were evaluated.
- The multi-stage radial compressor was found robust to the pressure dynamics studied.
- Air flow was maintained positive without entering into severe deep surge conditions.

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ABSTRACT

A better understanding of turbulent unsteady flows in gas turbine systems is necessary to design and control compressors for hybrid fuel cell-gas turbine systems. Compressor stall/surge analysis for a 4 MW hybrid solid oxide fuel cell-gas turbine system for locomotive applications is performed based upon a 1.7 MW multi-stage air compressor. Control strategies are applied to prevent operation of the hybrid SOFC-GT beyond the stall/surge lines of the compressor. Computational fluid dynamics tools are used to simulate the flow distribution and instabilities near the stall/surge line. The results show that a 1.7 MW system compressor like that of a Kawasaki gas turbine is an appropriate choice among the industrial compressors to be used in a 4 MW locomotive SOFC-GT with topping cycle design. The multi-stage radial design of the compressor enhances the ability of the compressor to maintain air flow rate during transient step-load changes. These transient step-load changes are exhibited in many potential applications for SOFC/GT systems. The compressor provides sustained air flow rate during the mild stall/surge event that occurs due to the transient step-load change that is applied, indicating that this type of compressor is well-suited for this hybrid application.

1. Introduction

Climate change, air quality challenges, and limited fossil energy resource availability, have spurred the consideration of more energy efficient and lower emitting energy conversion strategies for stationary power plants. Existing power plant technologies include gas turbines, steam turbines, the very popular combined cycle that includes both, and reciprocating engine power plants. Integrated hybrid systems have the potential to operate at higher efficiency than a fuel cell or gas turbine alone. Solid oxide fuel cells (SOFC) are electrochemical devices that convert the chemical energy contained in fuel directly into electrical energy through electrochemical reactions. SOFC power plants have been proven as an alternative power generation technology in electric utility applications and have been used in a variety of residential, commercial, and industrial applications. These types of power generation plants have also been evaluated and advanced theoretically in both locomotive, stationary and unconventional applications [1–8]. SOFC systems have operated on various types of fuels such as CO, natural gas, hydrogen (H_2), propane (C_3H_8) landfill gas, diesel and JP-8 [9–12]. SOFC power systems operate at higher temperatures than other types of fuel cells such as proton exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC) and molten carbonate fuel cells (MCFC), which are also used widely in stationary and transportation (PEMFC only) applications [13,14].

Hybrid fuel cell-gas turbine (FC-GT) systems provide clean

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energy at high efficiency [15]. The only turbo-machinery device that has been previously tested for hybrid fuel cell-gas turbine systems has been micro gas turbine generator (MTG) technology. Previously, MTG technology has been demonstrated as integrated with a high temperature SOFC and MCFC. In a given size class FC-GT hybrid power systems posses the highest efficiency and lowest emissions of all fossil fueled power plants [16]. In the future, SOFC-GT hybrid systems are one of the most promising technologies for meeting US Department of Energy (DOE) goals [17] for: 1) higher energy efficiency, 2) lower environmental pollution, 3) electricity at a competitive cost, and 4) integration with CO_2 capture and sequestration strategies. The potential for integration with coal gasification and inherent CO_2 separation advantages of high temperature fuel cell systems make SOFC-GT systems attractive for integrated gasification fuel cell (IGFC) power plants [18,19]. Some of the hybrid fuel cell-gas turbine challenges that have been identified and investigated previously [20,21] include: compressor surge, transient control, designing a proper heat engine for integration with the fuel cell, and difficulty of matching gas turbine's pressure ratio and mass flow rate with the SOFC pressure ratio and mass flow rate.

2. Stall/surge in a compressor

Placing the fuel cell in the high pressure section between the compressor and turbine increases the fuel cell efficiency by increasing the reactant partial pressures and lowering some polarization effects. The topping cycle design that is used for dynamic simulations in this study, introduces the need for a pressure vessel of significant volume and increases the potential for compressor stall/surge. Under steady-state conditions the compressor supplies a specific mass flow rate of air at every combination of shaft speed and pressure ratio. These values are typically normalized and compiled into tables or plotted in compressor maps. Compressor performance in gas turbines is limited by two main lines that are typically plotted on compressor maps: 1) a choke line at high air flow rate and, 2) a surge line at low air flow rate. The surge limit depends upon the compressor design and system configuration and especially upon the pressure dynamics downstream of the compressor. The dynamics of compressor surge/stall are significantly affected by introducing a fuel cell in the place of a combustor, making it difficult to predict surge. Reaching the surge limit might reduce the compressor performance temporarily or permanently and could introduce violent pressure and physical perturbations during stall/surge operation that could damage fuel cell. Therefore, control strategies are needed to keep the compressor performance in safe operating condition away from surge line (often called the surge margin).

At specific pressure ratios and shaft speeds compressor surge occurs when reversal of flow direction is caused by excess back pressure on the compressor. The series of operating points that result in a surge event are collectively grouped into the surge line that is plotted on compressor maps [22]. Such surge events are often followed by compressor stall and highly dynamic and stressful compressor conditions that can cause a complete mechanical failure of th fuel cell, gas turbine and/or the entire hybrid system. Researchers at the National Energy Technology Laboratory (NETL) have showed the benefits of compressor bleed and cold air bypass for controlling the compressor mass flow rate during transient behavior [16]. The HYPER hybrid system simulation facility was able to emulate hybrid systems in the range of 300 kW–900 kW. The thermal management of the fuel cell improved through controlling the cathode air flow during the load transient operation. The increased pressure losses introduced by the heat recuperation and the large cathode volume between the compressor and the turbine, were challenging during the hybrid system startup [23]. In that study, the compressor bleed air was used to avoid the compressor surge during the hybrid system startup. Ferrari et al. designed and installed an SOFC-GT physical emulator in the framework of a European Integrated Project [24]. The focus of their study was to minimize the viscous pressure loss in order to: 1) Reduce the unbalance between the compressor and the expander, 2) Maintain an accurate measurement, and 3) Have an effective plant efficiency. A modular high temperature volume was designed using computational fluid dynamics (CFD) tools to achieve a high uniformity in the flow distribution inside the volume and to minimize the pressure losses. The paper concluded that surge occurred during the shutdown for a particular configuration.

In another study, strategies to avoid surge or excessive stress during the start-up and shutdown phases were proposed [25], which lead to the finding that a new control strategy was required for managing the valve responsible for controlling turbine inlet temperature during the hybrid system start-up and shutdown emulation. McLarty et al. studied the dynamic operation of an SOFC-GT topping cycle and showed that the pressurized hybrid topping cycles exhibited increased stall/surge characteristics particularly during off-design operation [26,27]. In another study by McLarty et al. controls were utilized to mitigate the spatial temperature variation and the stall risk during load following [27]. The results showed that using the combined feed-forward, PI and cascade control strategy, 4:1 (SOFC) turn-down ratio could be achieved and a 65% efficiency could be maintained. Stiller et al. suggested that specific incidents should be avoided for safe operation of hybrid systems [28]. Some of these incidents are: compressor stall/surge or cell degradation due to thermal cracking or high temperatures, carbon deposition and anode compartment blocking, and backflow of gas from the burner to the anode, exposing the anode to oxygen. In that study, a new control strategy for managing the valve was used to generate the requested inlet temperature ramp during the hybrid system start-up and shutdown emulation.

Roberts et al. have mentioned some important disturbances in the hybrid carbonate fuel cell-gas turbine systems due to changes in the ambient temperature, fuel flow variation induced by supply pressure disturbances, fuel composition variability, and power demand fluctuations [29]. In that study, the predicted fuel cell operating temperature, fuel utilization, fuel cell and GT power, shaft speed, compressor mass flow and temperatures in the cycle were considered as the controlled response to the fuel cell voltage increase. Panne et al. demonstrated the steady state analysis of an SOFC-GT hybrid cycle test rig [30]. The cycle could be evaluated without the risk of damaging the cell. The effects of the ambient conditions or the pressure losses were investigated. The maximum compressor pressure ratio, the supplemental fuel mass flow and the SOFC air bypass were the three different limitations in the choice of cycle configuration. The additional pressure losses and piping had a significant impact on the surge margin. Hilderbrandt studied the compressor sensitivity analysis of the transient SOFC-GT-HS operation [31]. The reduced Moore and Greitzer model was used for the compressor modeling, showing that the transient part-load operation was sensitive to the characteristics of the compressor speedlines and the load change procedure. In another study, it was stated that at the shutdown with no control strategy, the slow thermal SOFC transients could result in the compressor surge [32]. Stiller studied a multi-loop control strategy for hybrid SOFC-GT system [28]. Fuel flow could be controlled by manipulating the fuel valve, while air flow could be controlled by manipulating the shaft speed, variable inlet guide vanes or variable compressor bleed. The effects of all three of these air flow control strategies on the system have been reported to be similar. In this study, shaft speed control by generator power manipulation was selected. System power was controlled by manipulating the SOFC current, fuel utilization was controlled by manipulating the fuel flow, air flow was controlled by manipulating the shaft speed and cell temperature was controlled by adjustment of the air flow setpoint.

Taccani et al. studied an experimental setup of SOFC-GT-HS at University of Trieste, Italy [33]. As a result of the relatively large volume of the pressurized portion of the plant and the shape of the stall characteristic of the compressors investigated, the fluid dynamic instabilities were found to occur in the plant. A surge could be detected in the off-design transient operation of the hybrid system during the plant regulation, start-up and shutdown. Sieros et al. examined the gas turbine behavior at the design point and the part-load operation regimes [34]. They mentioned that the prediction of surge was not reliable on the 1-D basis (i.e., the actual surge margin might be smaller than the predicted one). Using the components with variable geometries was suggested in that study. The literature suggests that two kinds of stall/surge are common in industrial compressors, which are labeled as "deep surge" and "mild surge". Deep surge is the result of complete reversal of flow in the compressor impeller at a specific time. This type of surge significantly reduces the compressor performance which could result in the complete system failure. The other more common type of the compressor surge is mild surge, which is characterized by an oscillatory mass flow rate at the impeller inlet and outlet caused by partial reversal of flow which causes reduced performance and efficiency of the compressor. However, mild surge is not as severe as deep surge.

3. Dynamic system model integrated with CFD simulation

This research addresses compressor stall/surge, one of the most significant challenges corresponding to commercialization of hybrid solid oxide fuel cell-gas turbine (SOFC-GT) systems, using a novel approach. This study models a multi-stage compressor using computational fluid dynamics (CFD) tools and subjects the CFD computations to dynamic inlet and outlet perturbations that result from a dynamic SOFC-GT system model. One of the main causes of compressor stall/surge in hybrid SOFC-GT systems is turbine inlet temperature rise due to the transient increase in power demand in a small period of time. As the power demand rises from steady state to a specific higher power in a short time period, turbine inlet temperature (TIT) increases so that the gas turbine can meet the power demand and ramp up to meet the higher air flow required. Thus, the mass flow rate at the turbine inlet decreases due to lower density while the mass flow rate from the compressor keeps building up pressure at the turbine inlet. As a result, reversal of flow in the compressor impellers can occur, which is recognized as deep surge. On the other hand, if the mass flow rate from the compressor persists during this pressure buildup phenomenon resulting in an oscillatory positive flow rate in the compressor impellers, then the phenomenon is recognized as mild surge.

The overall mechanism of stall/surge in a compressor due to the increase in turbine inlet temperature (TIT) has been previously studied by McLarty et al. [35]. Other researchers have addressed stall/surge in hybrid SOFC-GT systems and developed control methods to address stall/surge issues in the compressor. In one study, Azizi et al. studied compressor surge in a 220 kW hybrid system [36]. They used a CFD model to characterize stall/surge in a single-stage centrifugal compressor. The feasibility of the compressor integration in the hybrid system was determined in that study.

The overall approach of this research is based upon dynamic modeling of a hybrid SOFC-GT system in MATLAB/Simulink software, in order to simulate the dynamics of turbine inlet pressure and compressor outlet pressure during system transient operation. The system-level dynamic modeling is followed by CFD modeling of a multi-stage compressor of a 1.7 MW gas turbine system to characterize the fluid dynamics properties throughout the compressor impellers during transient operation. The simulated compressor fluid dynamics can then determine whether the compressor operation can feasibly avoid deep stall/surge in the hybrid SOFC-GT system. Transient dynamic CFD results from simulation of the 1.7 MW gas turbine are then analyzed to determine whether these types of multi-stage centrifugal compressors could be used in future SOFC-GT applications that require transient operation. For the first time, this study: 1) evaluates whether the previously developed control methods for safe operation of radial compressors really do lead to mild surge/stall in a particular compressor design; 2) informs whether the hybrid system control methods can be applied to centrifugal compressors of similar design, and 3) presents insights into the compressor fluid dynamics during transient operation that are relevant to any similar industrial compressor used in a hybrid SOFC-GT system.

4. Plant description

4.1. Dynamic hybrid system model

Fig. 1 shows the model of a 4 MW hybrid power generation system that has been previously developed at the National Fuel Cell Research Center (NFCRC) at the University of California, Irvine using MATLAB/Simulink tools. This model was used to show that such systems, when properly designed and controlled, possess higher efficiency than previously tested SOFC-GT systems in power generation applications. The model consists of a compressor, a turbine, a blower, an SOFC, a combustor, three mixers and several bypass valves (one for fuel cell bypass and the others for heater bypass). This model has been previously studied for different applications of SOFC-GT hybrid systems (see, for example [26,27,35,37]).

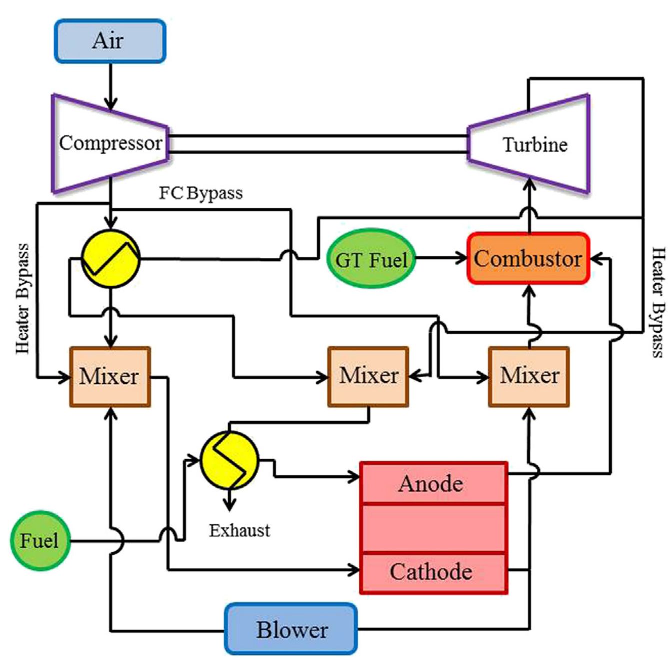

Fig. 1. Hybrid SOFC-GT system power plant schematic [35].

5. Turbomachinery model

Since the CFD computational time for simulating the turbomachinery is much larger than the time required for the dynamic simulation of the plant, a separate set of turbomachinery equations are used in the dynamic model in order to solve the transient pressure dynamics of the system. These equations have been previously used by McLarty et al. [35]. Input parameters of the compressor were the ambient temperature, the species concentrations, the shaft speed and the inlet/exit pressures. The ambient air pressure was assigned to the inlet pressure. The outlet pressure was found by backward solving of the pressure loss through the other components of the system. For the compressor, two conservation of energy models were considered [22]. The first was regarding the working fluid alone and the second included the compressor solid mass.

6. Fluid mechanics problem

The schematic of the fluid mechanics problem that is solved in this research is shown in Fig. 2. It consists of a diffuser between the two impellers (rotating parts of the compressor). Deep surge is the phenomenon when the pressure at the plenum is high enough that it could result in a complete reversal of the flow in the impeller. The diffuser between the two impeller stages resembles the plenum volume for the front impeller. The plenum volume for the rear impeller is replaced by the simulated pressure variation over time from the system dynamic model that includes dynamic simulation of the large volume of the fuel cell between the simplified (compressor map and turbine map) dynamic model of the turbomachinery (see [35]).

Eq. (1) explains the pressure gradient of the plenum volume over time, which accounts for the accumulation of mass that occurs in this volume when stall/surge is approached. The equation expresses the conservation of mass and isentropic expression for speed of sound, where c is the speed of sound and V_p is the volume of the plenum.

$$\frac{dP}{dt} \propto \frac{c^2}{V_p}(\dot{m}_2 - \dot{m}_e) \tag{1}$$

7. Applied control strategies

The modeling approach couples a dynamic system model for determining the hybrid system and compressor exit pressure dynamics that are supplied to a computational fluid dynamics (CFD) approach for resolving the fluid flow dynamics through the compressor. The dynamic system model uses a simplified geometrical representation of the solid oxide fuel cell integrated into the system with heat exchangers, a reformer and a gas turbine. The large volume between the compressor and the turbine causes mass accumulation and produces pressure dynamics during dynamic operation of the hybrid system. The approach is patterned after that which was previously developed at NFCRC [26,27,35,37]. Various control algorithms are applied to the dynamic system model to prevent deep surge in the compressor. The control system is suited for a hybrid system and depends upon the particular configuration and individual components in the system. The control strategy includes cascade controllers (with feed-back feed-forward strategies) to manipulate all of the control variables in hybrid system. Four system states and two electrical outputs are used as the feedback parameters in order to control the hybrid system.

The combined actions of the controllers can broaden the operating range of the hybrid system and decrease the transient response dynamics during pressure, temperature, fuel and other perturbations including load following. The control strategy measures five system states and uses five controllers to actuate three air valves, the guide vane angle of the gas turbine, two fuel valves (one to the fuel cell and the other to the anode tail-gas oxidizer), the fuel cell current and the gas turbine generator load. Fig. 3 shows the power demand and the power generated by the SOFC stack and the gas turbine over a 10,000 s time period. The SOFC stack and the gas turbine generate 2.2 MW and 800 kW nominal power respectively, at steady state conditions. After the hybrid system reached steady state operation, a step change increase in power demand was applied at a time of 1000s as shown in Fig. 4, which led to the pressure perturbation of interest that is studied in the CFD model.

The combined approach with cascade feed-forward feed-back control applied to the hybrid model enables rapid load following at high efficiency, but it does lead to the pressure dynamics shown in Fig. 4a,b shows the operation of SOFC-GT system at steady state mode. The operating point shows the performance of the system in safe mode as it is below the surge line. The point is close to the surge line which leads to system high efficiency. However, operation of the system in that region might be problematic without knowing the detailed fluid behavior in the compressor. Therefore, more detailed fluid mechanics modeling is required to address the type of the surge in dynamic mode that may result in complete system failure.

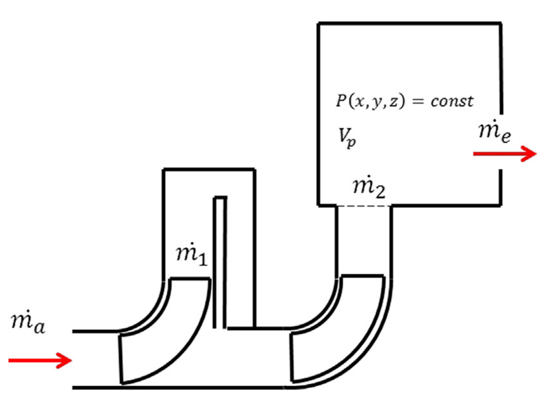

Fig. 2. Schematic of plenum at the inlet of turbine.

8. Transient dynamic simulation

In this paper, a power demand profile used by Martinez et al. [1] is used in order to investigate the compressor behavior during a sudden increase in the power demand. Due to the complexity of the computation and turbomachinery complexity, only one step of the power demand profile is considered in the CFD simulations of this study. The step power demand from 3 MW to 3.5 MW is applied to the dynamic model, and the pressure of the plenum node at the turbine inlet is solved in the MATLAB/Simulink platform. As the power demand rises from steady state at 3 MW–3.5 MW in a short time period, the turbine inlet temperature (TIT) increases so that the gas turbine and fuel cell could ramp up to ultimately meet the power demand. The period around 1000s shown in Figs. 3 and 4 present some of the dynamic system model results that are used as inputs to the CFD model.

9. Turbomachinery fluid dynamics simulation

Turbomachinery CFD modeling is used to explore and

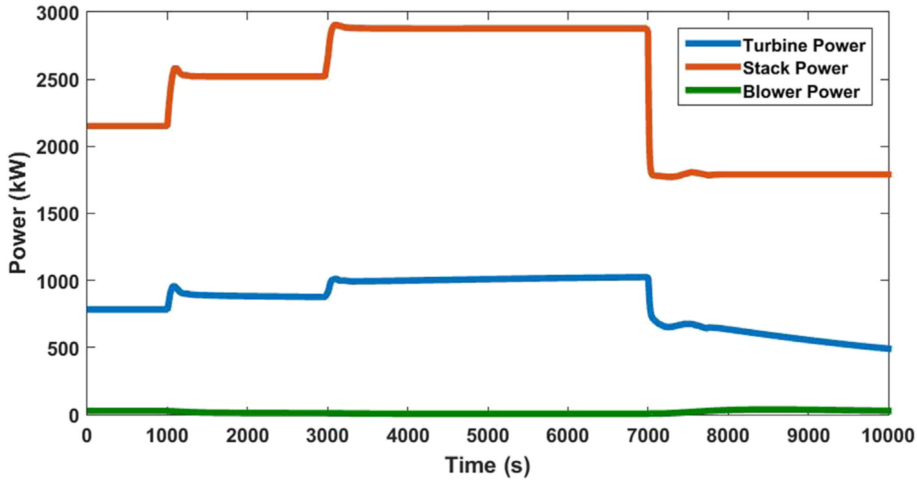

Fig. 3. Power generation of SOFC and gas turbine in the SOFC-GT hybrid system.

understand the stall/surge phenomenon in the same 4 MW hybrid fuel cell-gas turbine system. CFD analysis is applied on a multi-stage compressor configuration and its operational feasibility to meet the hybrid locomotive system step power demand increase observed during transient operation. The gas turbine design that could be integrated with an SOFC to produce the power levels

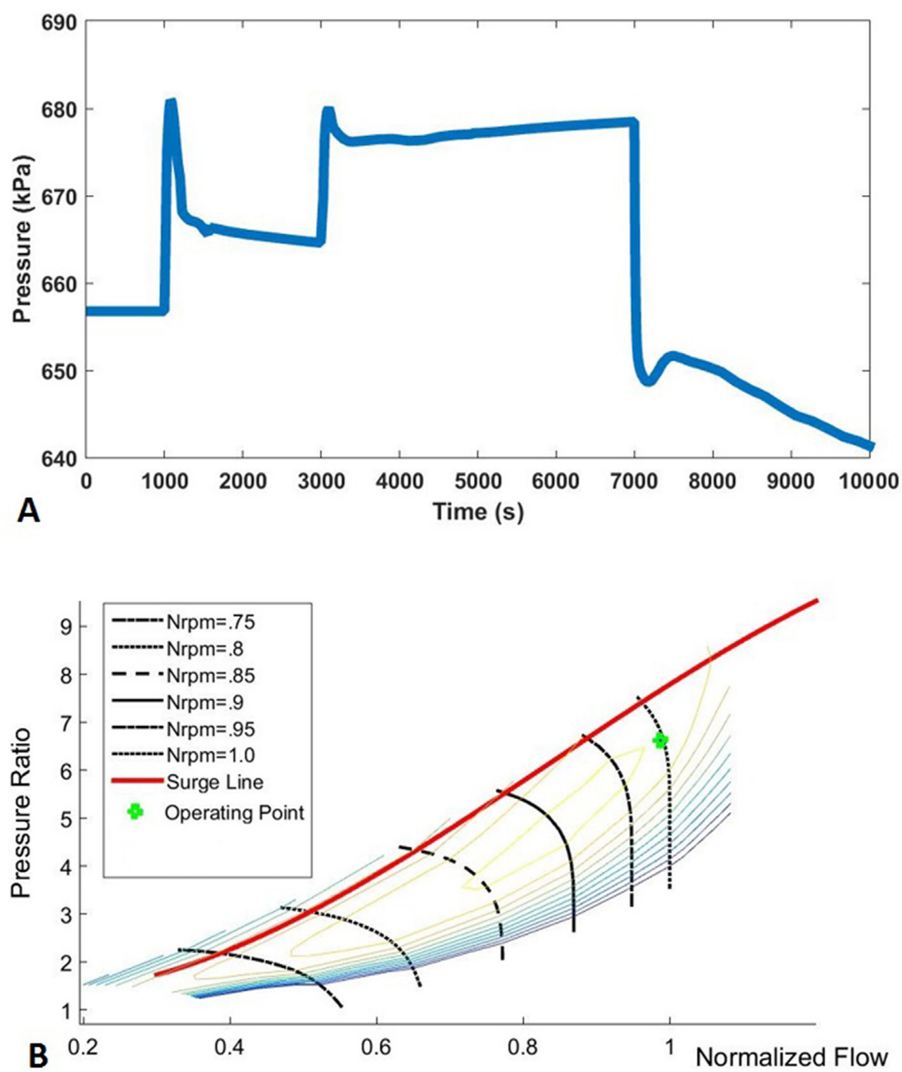

Fig. 4. A) Turbine inlet pressure (TIP) variation as the power demand changes. B) compressor map showing design operating point for a 4 MW hybrid SOFC-GT system at steady state.

required by the system include the multi-stage design of a compressor that is similar to the 1.7 MW Model GPB15/17 gas turbine manufactured by Kawasaki Industries [38]. This choice of compressor is based upon selecting turbomachinery that can approximately produce 20% of the net hybrid system power and match the air flow requirements of a corresponding SOFC. The design air mass flow rate required for the 4 MW hybrid system is 7 kg/s which is in the range of mass flow rates that the 1.7 MW gas turbine can deliver. Using this design mass flow rate, the SOFC-GT hybrid model design conditions are calibrated for the 40,000 rpm (design rotational speeed) rotor condition. The blades and diffuser are sized for the net 7 kg/s air mass flow rate at 40,000 rpm.

10. Geometry modeling

Due to their complex geometry, centrifugal compressors can be difficult systems to analyze using CFD. Specifically the multi-stage centrifugal compressor has a mid diffuser section that makes additional interface connections in the geometry. The simulation of these connections leads to a slower rate of solution convergence. The configuration considered in this study, includes two fast rotating impellers coupled to a stationary diffuser located between the impellers. In order to simulate each compressor stage, two sections (i.e., the rotating impeller and the stationary diffuser) must be modeled together. The impeller blade was designed for an overall pressure ratio of 3, so that the two impellers generate an overall pressure ratio of 9, and a rotating speed of 40,000 rpm. The geometry consists of two impellers and a diffuser located between the two impellers. In order to reduce the computational costs, full symmetrical boundary conditions are used to model only one flow passage of the compressor. Each of the rotating and stationary sections were meshed independently. The impellers were meshed by the structured hexahedral method in ANSYS TurboGrid meshing software [39] while the diffuser was meshed using unstructured tetrahedrals with boundary layer refinements. The three separate mesh grids were connected by defining proper interfaces between the rotor and diffuser sections.

11. Boundary conditions

Stage averaging is used as a method of interface connection between the diffuser and impeller. In this method a circumferential averaging is applied at the interface between the rotor and stator. In order to apply correct boundary conditions to the fluid domain, a subsonic uniform air flow rate boundary condition with atmospheric pressure and temperature is applied to the inlet. The turbulent intensity was set to 5% at this boundary. The pressure dynamic perturbation that resulted from step load change applied to the hybrid SOFC-GT system simulation, is applied to the domain outlet. Since the diffuser domain is stationary and the impellers are rotating, two interface boundaries are defined between the rotating impellers and the stationary diffuser.

12. Fluid dynamics model

A Reynolds Averaged Navier-Stokes (RANS) based model of shear stress transport (SST), $k-\omega$ is used to close the system of equations that describe the turbulent flow that is simulated. Using the $k-\omega$ model instead of the $k-\varepsilon$ model allows for better resolution of boundary layers, especially under adverse pressure gradients. However, in the current study, the SST model was more difficult to converge than the $k-\varepsilon$ model. Nonetheless, the SST model is known to better simulate wall bounded aerodynamic flows, e.g, airfoils, compressors, turbines, and flows with separation due to adverse pressure gradients. In addition, the SST closure model is used to reduce the boundary condition sensitivity. ANSYS CFX [39] was chosen as the simulation platform due to the proven ability to tackle complex turbomachinery problems faced in the gas turbine industry. Eq. (2) to (5) show the basic fluid dynamics equations that are solved in this study [40].

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=P-\beta^{*}\rho\omega k+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right] \quad (2)$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho u_j\omega)}{\partial x_j}=\frac{\gamma}{\nu_t}P-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_j}\right]+2(1-F_1)\frac{\rho\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j} \quad (3)$$

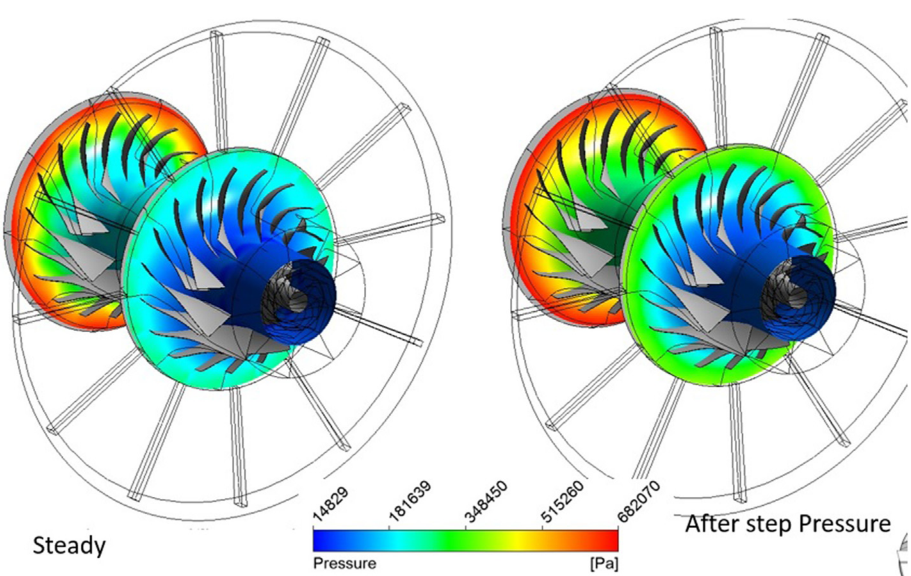

Fig. 5. Pressure distribution in the flow domain on the front and rear impellers of the multi-stage compressor.

$$P = \tau_{ij}\frac{\partial u_i}{\partial x_j} \quad (4)$$

$$\tau_{ij} = \mu_t\left(2S_{ij} - \frac{2}{3}\ \frac{\partial u_k}{\partial x_k}\delta_{ij}\right) - \frac{2}{3}\rho k\delta_{ij} \quad (5)$$

In order to obtain good convergence, first the solver converged to the steady state solution. Following the stationary solution, the transient boundary condition was applied to the model and the system was solved for each time step in the short period of time that the system dynamics produced the pressure perturbation.

13. Stall/surge results

During the initial dynamic analysis of the hybrid system based on typical compressor maps, the operating point was below the surge line and in the safe region as shown in Fig. 4b. The implemented control algorithms produced system operating dynamics that met the power demand dynamics without allowing the compressor to operate in a deep surge condition. However, the fluid dynamics of a realistic industrial compressor performance must be

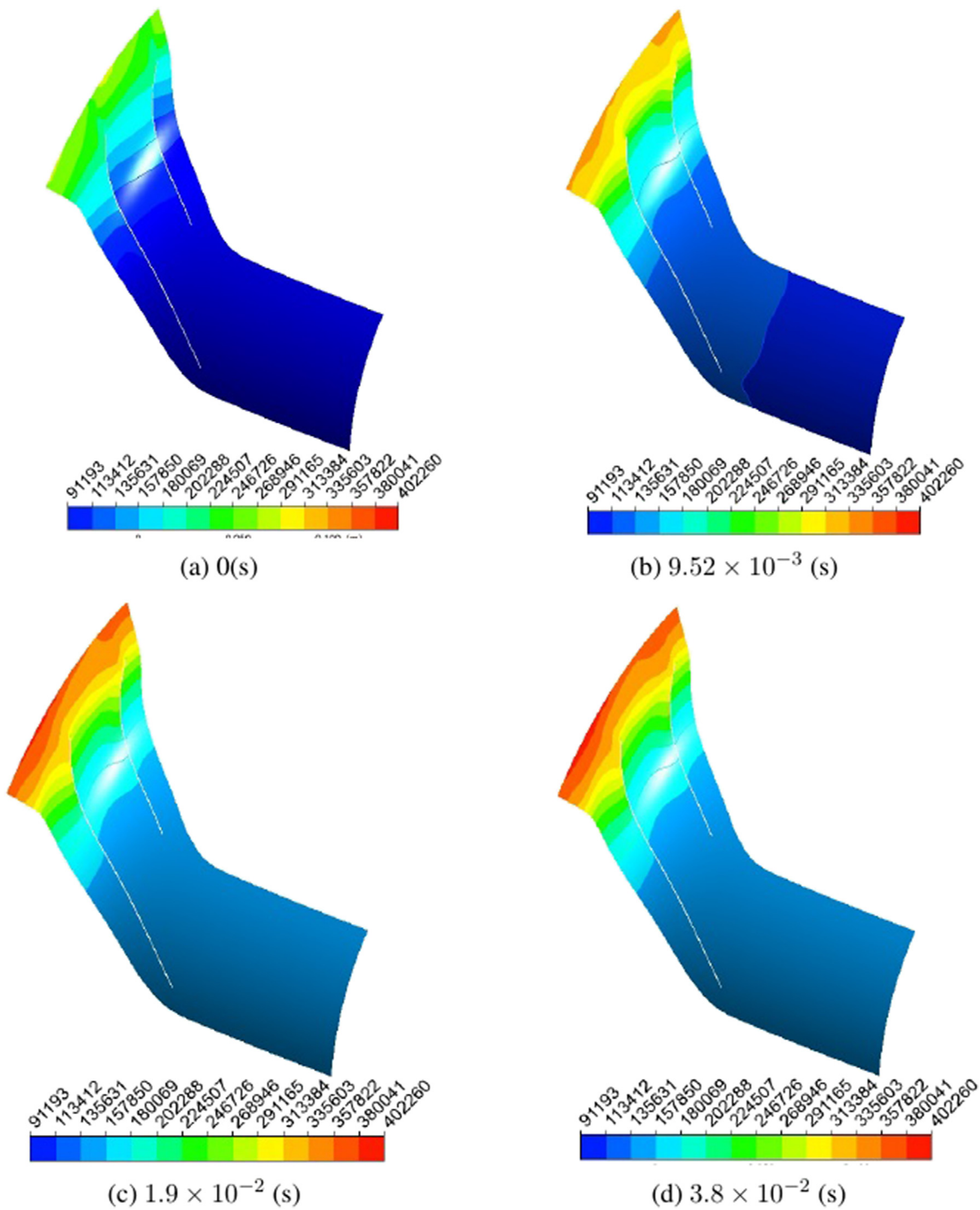

Fig. 6. Pressure development on the front impeller's shroud.

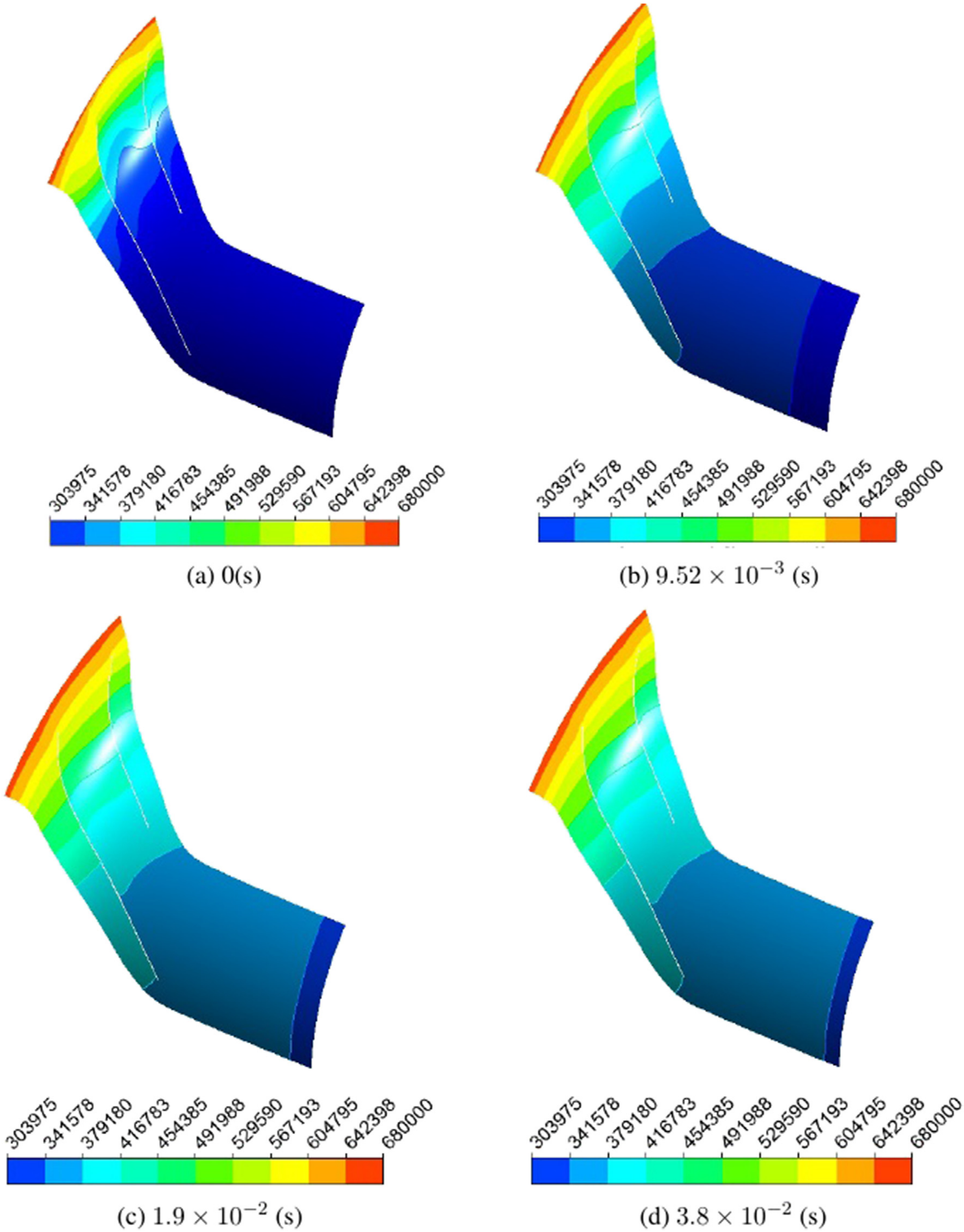

Fig. 7. Pressure development on the rear impeller's shroud.

investigated for conditions corresponding to this dynamic operation of the hybrid system. This is the main contribution of the current effort.

The dynamic pressure step perturbation due to the transient power demand variation in a small time period is applied to the rear impeller outlet. This perturbation results in the development of higher pressure in the diffuser and impellers as a function of rotor revolution (time). The pressure in the diffuser and the impellers increases over time during the transient CFD computation. High pressure development takes time to reach the front impeller due to the stabilized flow in the middle stationary diffuser located between the two rotating impellers. The pressure development shown in Fig. 5 took 25 rotor revolutions. The disrupted velocity vectors that are formed on both impellers reduce the compression efficiency. Higher pressure on the rear impeller follows the fuel cell pressure step increase, which over time (over a number of rotor revolutions) results in higher pressure in the diffuser and the front impeller. Ongoing positive mass flow rate through the front

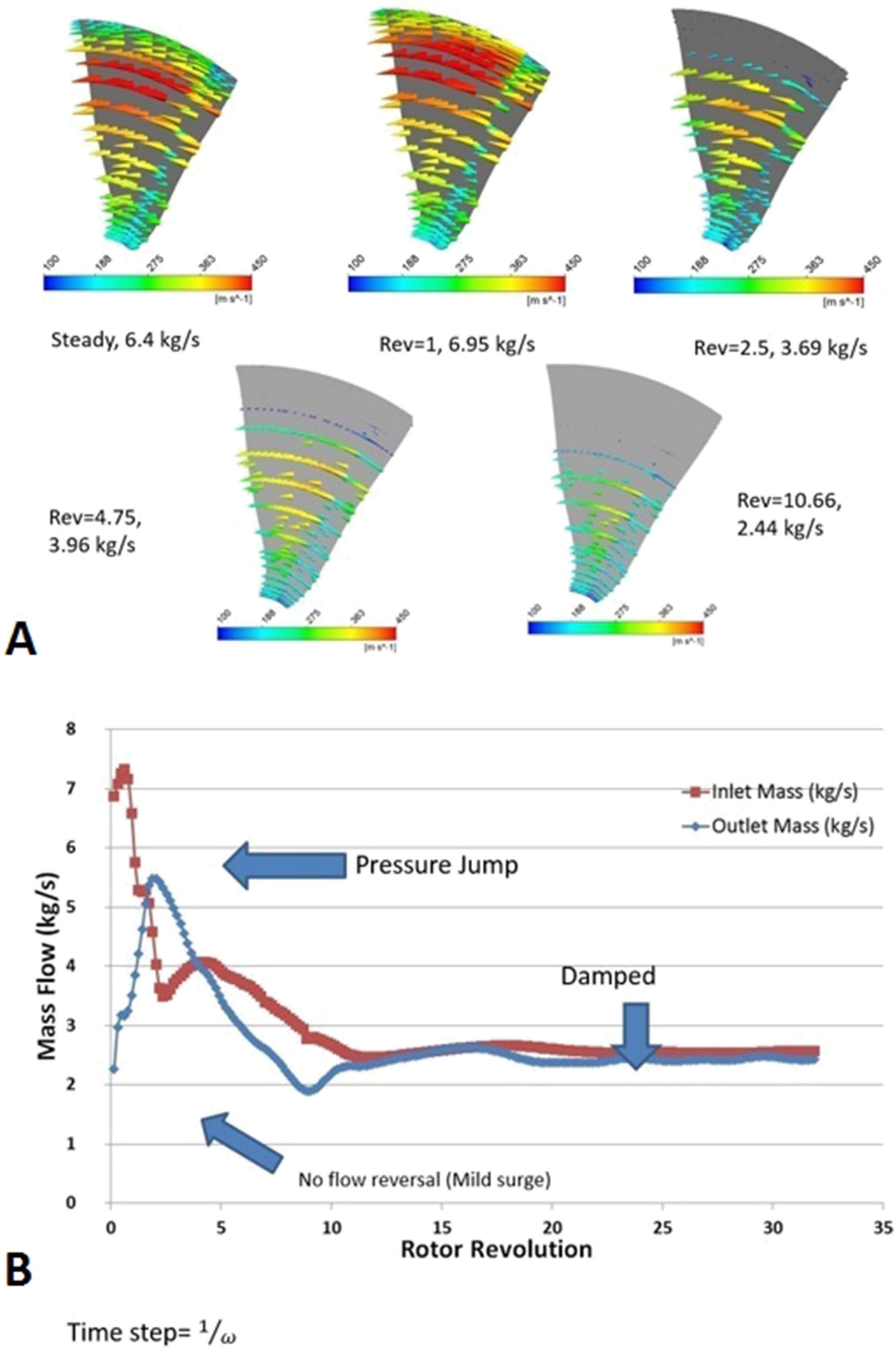

Fig. 8. (A) Front impeller inlet velocity distributions at various rotor revolutions (steady through Rev = 10.66), (B) Total compressor inlet and outlet mass flow rate versus time.

impeller and an increase in back pressure on the rear impeller causes a pressure accumulation in the diffuser, which subsequently causes a secondary mild stall/surge in the front impeller.

The higher pressure at the rear impeller outlet causes lower velocity in the rear impeller and consequently lower mean average velocity in the front impeller. Due to the higher pressure, temporary instabilities in the flow direction occur at the rear impeller inlet. Lower tangential velocity at the front impeller outlet causes lower mass flow rate at the front impeller inlet. High outlet pressure causes temporary blockage of a portion of the air flow at the impeller outlet. In addition, due to the high pressure, temporary instabilities in the flow direction occur in the region from the impeller inlet toward the leading edge. Vortices form on the blade that reduce the impeller compression efficiency. During the computational period, the radial velocity at the impeller outlet decreases. As a result, the mass flow rate leaving the rear impeller decreases as representative of mild compressor stall/surge. Fig. 6 and 7 show the pressure development on the shroud and the mild surge dynamics over the front and rear impellers over time. Comparing these figures, note that the pressure on the rear impeller reaches a steady state condition faster than the front impeller. In addition, the significant volume of the diffuser between the two impellers, delays the pressure increase in the front impeller. Thus, whenever a fast transient power demand is required, the mid-diffuser delays the initiation of stall/surge on the front impeller and lets the rear impeller return to normal operation before the second stall/surge event begins in the front impeller. Therefore, this multi-stage configuration allows a time delay between the two stall/surge phenomena that increases the stability of operation during this pressure perturbation dynamic. This results in lower risk of hybrid system failure.

Fig. 8A shows the velocity distributions corresponding to the mild surge event on the front impeller inlet for the steady-state case and for various rotor revolutions (Rev = 1, 2.5, 4.75, and 10.66). These velocity profiles show a sustained positive mass flow rate during the hybrid SOFC-GT gas turbine transient operation as shown by the total mass flow rate versus time plot of Fig. 8B. Note that this dynamic operation of the compressor was produced in response to the pressure dynamic perturbation of the system model that was applied as boundary condition to the CFD model. Following the pressure step change, the system reaches a stead-state operation and positive mass flow rate continues throughout the front and rear impellers without significant flow reversal.

At steady state operation, the net mass flow rate is 6.4 kg/s, which is close to the design mass flow rate of the scaled gas turbine (similar to Kawasaki gas turbine) that is simulated. As the diffuser outlet pressure rises, the net mass flow rate decreases. However, the tangential velocity increases. The outlet mass flow rate decreases to the point of steady mass flow rate at the impeller outlet, which is the normal operating condition. At the 20th rotor revolution, the net air mass flow rate converges to a steady state and retains its constant positive value during the rest of this short period of hybrid SOFC-GT system operation. These results show that this type of industrial compressor can handle the type of transient pressure perturbation that a hybrid system could introduce quite well. However, control algorithms must be developed and applied subsequently in the system model to ramp the air flow rate back up to the required flow rate over time.

The dynamic response of the rear impeller that corresponds to that of the front impeller shown in Fig. 8 are not shown for brevity. As the outlet pressure increases, the flow velocity on the rear impeller gradually decreases at the trailing edge. Some locations of zero velocity are developed from the trailing edge to the leading edge. This situation is accompanied by the vortices that are formed along the blades and the splitters that correspond to local flow reversal.

14. Discussion of stall/surge results

The mass flow rates are calculated at the inlet and outlet of the multi-stage compressor as a function of the number rotor revolutions (time). Note that, in the multi-stage configuration there is a net and sustained positive mass flow rate through the compressor outlet as the pressure transient perturbation is applied. The compressor responds with mild surge behavior to eventually return to a new steady state. Notice that the 32 rotor revolutions simulated in the CFD simulation correspond to 0.05 s of hybrid system operation. After the compressor relaxes from the applied pressure dynamic, the turbomachinery will be “spun-up” (primarily by increasing TIT) over time to deliver the new air flow rate required by the hybrid system. In the system model, this transient period lasts on the order of seconds. During this period the pressure dynamics could also be simulated using the CFD model developed in this work. However, since the dynamics are relatively slow under these circumstances, CFD simulation of the compressor may not be required.

15. Summary and conclusions

In this effort, one of the major hybrid SOFC-GT system challenges, compressor stall/surge, which can significantly affect hybrid SOFC-GT system performance during sudden power demand perturbations, was investigated. A multi-stage compressor model is developed that has a similar configuration to that available in an industrial multi-stage compressor (e.g., the 1.7 MW Kawasaki gas turbine model GPB17). This type of compressor could possibly be used in a 4 MW hybrid SOFC-GT system. The transient operation of this type of industrial centrifugal compressor is analyzed using computational fluid dynamics (CFD) tools, which provide insights regarding the flow distribution in the compressor impellers during dynamic hybrid system operation. A transient pressure boundary condition that resulted from a load perturbation applied in the hybrid system dynamic simulation was applied to the CFD model of the compressor. The CFD model resolved the compressor dynamics that occurred in response to the pressure perturbation near the stall/surge limit line. The multi-stage compressor was shown to be robust to the investigated pressure dynamics (able to handle pressure perturbation of interest without going into deep stall/surge), making it suitable for use in hybrid SOFC-GT applications.

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References

[1] Andrew S. Martinez, Jacob Brouwer, G. Scott Samuelsen, Feasibility study for SOFC-GT hybrid locomotive power: Part I. Development of a dynamic 3.5 MW SOFC-GT FORTRAN model, J. Power Sources 213 (2012) 203–217.
[2] Andrew S. Martinez, Jacob Brouwer, G. Scott Samuelsen, Feasibility study for SOFC-GT hybrid locomotive power part II. System packaging and operating route simulation, J. Power Sources 213 (2012) 358–374.
[3] Subhash C. Singhal, Solid oxide fuel cells for stationary, mobile, and military applications, Solid State Ionics 152 (2002) 405–410.
[4] S. Samuelsen, J. Brouwer, Fuel cell/gas turbine hybrid, Encycl. Electrochem. Power Sources (2009) 124–134.
[5] L. Barelli, G. Bidini, A. Ottaviano, Part load operation of SOFC/GT hybrid systems: stationary analysis, Int. J. hydrogen energy 37.21 (2012) 16140–16150.
[6] Fuel Cells for Buildings and Stationary Applications Roadmap Workshop, US Department of Energy, College Park, MD, USA, 2002.
[7] Dincer Ibrahim, C. Ozgur Colpan, Introduction to Stationary Fuel Cells Solid

oxide fuel cells: from materials to system modeling, R. Soc. Chem. (2013) 1–25.
[8] Mohammad Ali Azizi, Jacob Brouwer, Derek Dunn-Rankin, Analytical investigation of high temperature 1kW solid oxide fuel cell system feasibility in methane hydrate recovery and deep ocean power generation, Appl. Energy 179 (2016) 909–928.
[9] K. Sasaki, et al., Multi-fuel capability of solid oxide fuel cells, J. Electroceramics 13 (1–3) (2004) 669–675.
[10] W.A. McPhee, et al., Direct JP-8 conversion using a liquid tin anode solid oxide fuel cell (LTA-SOFC) for military applications, J. Fuel Cell Sci. Technol. 8.4 (2011) 041007.
[11] J. Staniforth, K. Kendall, Cannock landfill gas powering a small tubular solid oxide fuel cell—a case study, J. Power Sources 86.1 (2000) 401–403.
[12] A. Lindermeir, et al., On-board diesel fuel processing for an SOFC–APU—technical challenges for catalysis and reactor design, Appl. Catal. B Environ. 70.1 (2007) 488–497.
[13] Ryan P. O'Hayre, Suk-Won Cha, Whitney Colella, Fritz B. Prinz, Fuel Cell Fundamentals, John Wiley & Sons, New York, 2006.
[14] Kaushik Rajashekara, Hybrid fuel-cell strategies for clean power generation, IEEE Trans. industry Appl. 41.3 (2005) 682–689.
[15] Xiongwen Zhang, et al., A review of integration strategies for solid oxide fuel cells, J. Power Sources 195.3 (2010) 685–702.
[16] Wolfgang Winkler, et al., General fuel cell hybrid synergies and hybrid system testing status, J. Power Sources 159.1 (2006) 656–666.
[17] A.D. Rao, G.S. Samuelsen, F.L. Robson, R.A. Geisbrecht, Power plant system configurations for the 21st century, in: ASME Turbo Expo 2002: Power for Land, Sea, and Air, American Society of Mechanical Engineers, 2002, January, pp. 831–844.
[18] Lisbona Pilar, Luis M. Romeo, Enhanced coal gasification heated by unmixed combustion integrated with an hybrid system of SOFC/GT, Int. J. Hydrogen Energy 33.20 (2008) 5755–5764.
[19] Matteo C. Romano, et al., Thermodynamic analysis and optimization of IT-SOFC-based integrated coal gasification fuel cell power plants, J. Fuel Cell Sci. Technol. 8.4 (2011) 041002.
[20] Jacob Brouwer. Hybrid Gas Turbine Fuel Cell Systems Handbook, National Energy Technology Laboratory.
[21] Sue Fuhs, Solid Oxide Fuel Cells & Hybrid, GE Hybrid Power Generation Systems.
[22] Dustin Fogle McLarty, Fuel Cell Gas Turbine Hybrid Design, Control, and Performance, University of California, Irvine, 2010.
[23] D. Tucker, L. Lawson, R. Gemmen, R. Dennis, Evaluation of hybrid fuel cell turbine system startup with compressor bleed, in: ASME Turbo Expo 2005: Power for Land, Sea, and Air, American Society of Mechanical Engineers., 2005, January, pp. 333–341.
[24] Mario L. Ferrari, et al., Hybrid simulation facility based on commercial 100 kWe micro gas turbine, J. Fuel Cell Sci. Technol. 6 (3) (2009) 031008.
[25] Mario L. Ferrari, et al., Hybrid system test rig: start-up and shutdown physical emulation, J. Fuel Cell Sci. Technol. 7.2 (2010) 021005.
[26] McLarty Dustin, Jack Brouwer, Scott Samuelsen, Fuel cell–gas turbine hybrid system design part I: steady state performance, J. Power Sources 257 (2014) 412–420.
[27] Dustin McLarty, Jack Brouwer, Scott Samuelsen, Fuel cell–gas turbine hybrid system design part II: dynamics and control.'' Journal of Power Sources 254 (2014) 126–136.
[28] Christoph Stiller, et al., Control strategy for a solid oxide fuel cell and gas turbine hybrid system, J. Power Sources 158.1 (2006) 303–315.
[29] R.A. Roberts, J. Brouwer, E. Liese, R.S. Gemmen, Development of controls for dynamic operation of carbonate fuel cell-gas turbine hybrid systems, in: ASME Turbo Expo 2005: Power for Land, Sea, and Air, American Society of Mechanical Engineers, 2005, January, pp. 325–331.
[30] T. Panne, A. Widenhorn, M. Aigner, Steady state analysis of a sofc/gt hybrid power plant test rig, in: ASME Turbo Expo 2008: Power for Land, Sea, and Air, American Society of Mechanical Engineers, 2008, January, pp. 463–472.
[31] A. Hildebrandt, M. Assadi, Sensitivity analysis of transient compressor operation behaviour in SOFC-GT hybrid systems, in: ASME Turbo Expo 2005: Power for Land, Sea, and Air, American Society of Mechanical Engineers, 2005, January, pp. 315–323.
[32] A. Hildebrandt, M. Genrup, M. Assadi, Steady-state and transient compressor surge behavior within a SOFC-GT-hybrid system, in: ASME Turbo Expo 2004: Power for Land, Sea, and Air, American Society of Mechanical Engineers, 2004, January, pp. 541–550.
[33] R. Taccani, D. Micheli, Experimental test facility for the analysis of transient behavior of high temperature fuel cell/gas turbine hybrid power plants, J. Fuel Cell Sci. Technol. 3 (3) (2006) 234–241.
[34] G. Sieros, K.D. Papailiou, Gas turbine components optimised for use in hybrid SOFC-GT systems, in: Proceedings of 7th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics. Athens, Greece, 2007.
[35] Dustin Fogle McLarty, Thermodynamic Modeling and Dispatch of Distributed Energy Technologies Including Fuel Cell–Gas Turbine Hybrids, 2013.
[36] Azizi, Mohammad Ali, Jacob Brouwer, Transient analysis of 220 kW solid oxide fuel cell-gas turbine hybrid system using computational fluid dynamics results, ECS Trans. 71 (1) (2016) 289–301.
[37] D. McLarty, Y. Kuniba, J. Brouwer, S. Samuelsen, Experimental and theoretical evidence for control requirements in solid oxide fuel cell gas turbine hybrid systems, J. Power Sources 209 (2012) 195–203.
[38] Kawasaki gas turbines-americas gas turbines power generation Technol. Appl.. A Present. by Kawasaki Gas Turbines, pp. 1-45.
[39] ANSYS® Academic Research, Release 16.0.
[40] Florian R. Menter, Two-equation eddy-viscosity turbulence models for engineering applications, AIAA J. 32 (8) (1994) 1598–1605.