# Development of a Bypass Catalytic Combustor for the Miniature Gas Turbine Burning Syngas

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## 1 Introduction

The combustion of low-heating-value gases becomes more important due to the expectation of premium fuel depletion. The synthesized gas (syngas), produced by gasification of coal, biomass, municipal waste et al., is regarded as one of the potential energy resources in the immediate future. After purification, the major energy sources of syngas come from $H_2$ and CO, with a ratio usually in the range of 0.5 to 2, and to a lesser extent, from methane. Because the heating-value content of syngas is usually low, the combustion of syngas causes a number of problems, of which the severe ones to be solved are the reduced combustion temperatures, and consequently, burning rates, narrow stability limits and low combustion efficiencies [1]. Catalytic combustion is known to provide an attractive way to enhance the stability of lean and low heating-value combustions while decreasing pollutant emission and without significant pressure loss. Although catalytic combustion is generally regarded as a clean and high efficiency combustion technique, challenges remain in the design of a practical catalytic combustion device, especially in a gas turbine combustor. The limited maximum operation temperature of the catalyst bed is the major issue to be considered in the gas turbine power generating device as the combustor exit temperature is directly related to the cycle thermal efficiency. The current commercial catalysts cannot survive in the high-temperature environment in a gas turbine combustor condition, and therefore the thermal efficiency is limited. The concept of hybrid combustion is proposed to prevent sintering and damage to the catalyst in most of catalytic combustors for gas turbine [2]. In the hybrid combustion, the catalytic reaction is used for the ignition and stabilization of lean and low-temperature gas-phase combustion with a high-efficiency conversion of fuel. Based on the above concept, several types of catalytic combustor were proposed, such as outer catalyst combustor, center catalyst combustor [3], two-stage rich-catalytic lean-burn combustion [4], catalytic pilot combustion [5] and so on.

In the present study, we develop a bypass catalytic combustor for syngas combustion in a miniature gas turbine. The bypass ratio and the catalyst bed design depend on the operation conditions of the miniature gas turbine and the relative gas phase ignition delay time at the downstream of the catalyst bed. The potential and feasibility of using bypass catalytic combustion in a miniature gas turbine, which burns syngas from coal gasification with $H_2$ and CO as the major components, are examined by numerical simulations by varying the design parameters of bypass ratio and pressure ratio. The stabilization factors of gas-phase reactions are also discussed in this study.

# 2 Modeling Methods

The syngas combustion in the bypass catalytic combustor is modeled by the CFD-ACE commercial code with multi-steps gaseous and surface reactions mechanism in this study. Two-dimensional Navier–Stokes equations for reacting flows along with energy and species conservation equations are solved in general non-orthogonal curvilinear coordinates. The flow code is coupled with the CHEMKIN software libraries, providing generality for treating chemically reacting mixtures of gases including multi-component diffusion and thermal diffusion. Surface chemistry is incorporated into the code using SURFACE CHEMKIN. The steady-state solution is computed in all cases. The chemical mechanism for synags reactions on a platinum catalyst used in the present study is identical to that developed by Deutschmann et al. [6] for methane. This mechanism contains 27 irreversible elementary steps (23 reactions including 1 duplicate reaction of $O_2$ adsorption) among 9 gas phase species and 11 surface species. The gas-phase reactions for syngas oxidation, the skeletal gas-phase reaction mechanism for methane-air by Smooke [7], is included in the simulation. The skeletal mechanism contains 16 chemical species and 36 reaction steps.

The bypass catalytic combustor consists of the center catalyst combustor with outer bypass channels and the downstream sudden-expansion gas-phase flame stabilizer. The catalytic reaction of the center catalyst is used for ignition and stabilization of downstream gas-phase combustion of the bypass mixture. The geometry used for modeling the bypass catalytic combustor is based upon a single channel monolith platinum catalyst and the surrounding stainless steel wall as bypass channels. Detailed geometry of a representative bypass catalytic combustor is shown in Fig. 1. Assuming axi-symmetry, the problem can be modeled by two-dimensional simulation with the radial domain from the centerline of the catalyst channel to the bypass channel. The boundary conditions are stated as follows. In terms of the suggestions reported in the literature [8], uniform velocity of the $H_2$/CO/air mixture, 10m/s and volume concentrations of $H_2$ 4%, CO 4% in air are specified at the inlet of the bypass combustor. The inlet temperature is 573 K. Adiabatic condition is prescribed on the outer wall of bypass channel due to the multi-channel construction in the practical device. The flow outlet is set as constant pressure condition, and an extrapolation scheme is adopted for other variables at the outlet boundaries in the numerical simulation. The thermal conductivities of stainless steel and cordierite ($2Al_2O_3{\cdot}MgO{\cdot}5SiO_2$) are also taken into account. Radiation heat loss is neglected in this analysis.

# 3 Results and Discussion

Figure 2 shows the calculated temperature profiles of the bypass combustor with various bypass and pressure ratios. The combustible mixture is first ignited by catalytic reaction near the leading edge along the catalyst channel. Heat produced from catalytic reaction immediately transfers to the other side of the channel wall through conduction that heats up the boundary layer of the bypass flow mixture and ignites the gas phase reaction of the bypass channel. The maximum temperature appeares in the downstream region of the catalyst outlet when the bypass ratio increases to 3 and pressure ratio is more than 2. The maximum catalyst temperature of all examined conditions can be maintained below the suggested temperature limitation, 1273K [2, 3]. The results indicate that the gas phase reaction can be ignited and stabilized at the downstream of the catalyst outlet under the high bypass ratio and high pressure ratio conditions. In addition, the comparisons of temperature profile between various bypass ratio cases show that the gas phase reaction of the bypass channel influences the downstream reactions. Under the higher bypass ratio condition, the downstream combustion reaction of the catalyst channel can be enhanced due to the enhanced heat transfer. The temperature profiles are dominated by the bypass ratio while the operation pressure remains constant. When the pressure ratio increases, the thermal boundary layer for both the catalyst channel and the bypass channel move approach the channel surface, but the downstream gas phase reactions are enhanced. The resultant contrast between the cases of pressure ratio 1, 2 and 3 reveals the competition between the surface and gas phase reactions. The temperature of gas phase near the channel surface becomes higher than the surface temperature that appeared in the case of pressure ratio 2. It implies that the surface reaction is inhibited as the pressure increases, and the gas phase reaction induced by surface reaction of catalyst wall can propagate far away from the surface. If the pressure is further increased, the energy produced by the surface reaction will be used just for self sustaining of the surface reaction and near wall gas phase reaction. Therefore, a stronger gas phase reaction obtained due to higher fuel concentrations at the downstream of catalyst outlet under high pressure conditions is inferred.

Figure 3 presents simulation results of reactant and product profiles under various conditions. In this figure, a significant difference of species distribution between hydrogen and carbon monoxide reactions is observed. A large number of hydrogen reactions occur and grow rapidly from the leading edge along the channel walls, including the catalyst wall and the inner bypass wall. In contrast to the high consumption of hydrogen, only a small amount of carbon monoxide can be burnt near the catalyst wall. The product, $H_2O$ distributes from the wall to the downstream near the catalyst outlet, and the concentrations increase with the bypass ratio. When the pressure ratio increases, the surface reaction of catalyst channel is inhibited, and the combustion reaction moves downstream. Hydrogen distributions extend to the downstream and more $H_2O$ are produced in the homogeneous reaction zone. For the reaction of carbon monoxide, both CO consumptions and $CO_2$ productions appear following the hydrogen reactions. Energy released from hydrogen reaction plays an important role to ignite carbon monoxide reaction and to sustain the subsequent reactions. The concept of hybrid combustion of syngas is achieved in this study and the feasibility of using bypass catalytic combustor for miniature gas turbine is achieved.

## 4 Conclusion

In this study, numerical simulations are performed to investigate the operation and performance of the bypass catalytic combustor under the miniature gas turbine conditions with various bypass and pressure ratios. The feasibility of using the bypass catalytic combustor for syngas in gas turbine is verified. Hydrogen in the syngas can be easily ignited on the surface by surface catalytic reaction in the leading edge of the catalyst channel and the heat generated leads to enhanced gas-phase reaction of carbon monoxide near the wall and extending downstream. Bypass ratio dominates the supplies of combustible mixture at the downstream of the catalyst outlet to stabilize the subsequent gas-phase reactions in the homogeneous reaction zone when the energy supply from the catalyst and bypass channels is high enough. Carbon monoxide of the syngas is mainly consumed in the downstream gas-phase reaction in homogeneous reaction region. Furthermore, the influence of the pressure ratio on the competition between surface and gas-phase reactions in the catalyst channel is also observed in this study. High pressure ratio inhibits the surface reactions and enhances the gas-phase reactions that can prevent the catalyst from overheat.

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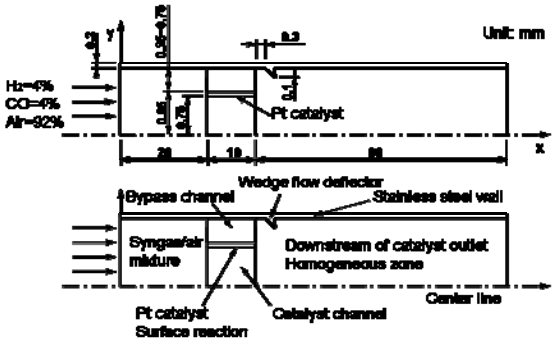


Figure 1. The illustration of the bypass catalytic combustor and the detailed dimensions used in the numerical models.

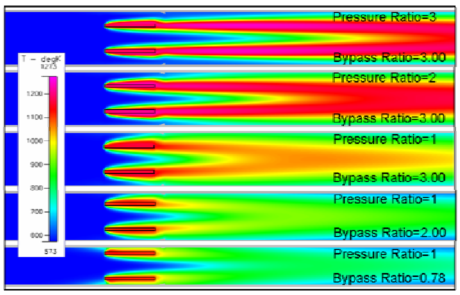


Figure 2. The predicted temperature profiles in various bypass ratios and pressure ratios, in which bypass ratio is defined as the area ratio of bypass channel/catalyst channel.

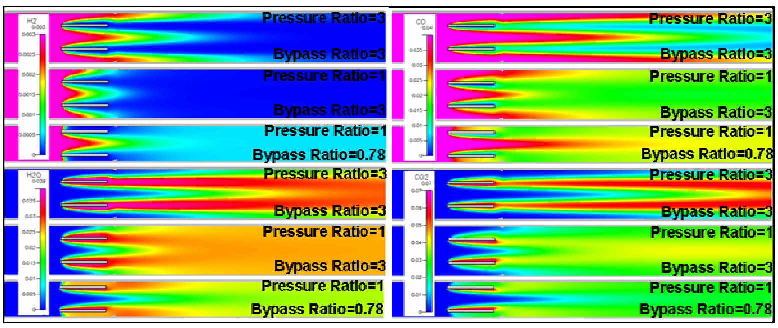


Figure 3. The predicted reactant and product profiles, $H_2$, $H_2O$, CO, and $CO_2$, under various conditions.