한국수소 및 신에너지학회 논문집(2005.9), 제16권 제3호
Trans. of the Korean Hydrogen and New Energy Society (2005.9), Vol. 16, No. 3, pp. 229~237

연료전지용 컴팩트형 개질기의 고성능화를 위한 고온 공기 연소 기술의 적용에 관한 연구

이경호, 권오채†
성균관대학교 기계공학부

A Numerical Study on a High-Temperature Air Combustion Burner for a Compact Fuel-Cell Reformer

Kyoung Ho Lee, Oh Chae Kwon†
School of Mechanical Engineering, Sungkyunkwan University
300 Chunchun-dong, Jangan-gu, Suwon, Kyunggi-do 440-746, Korea

ABSTRACT

A new burner configuration for a compact fuel-cell reformer with a high-temperature air combustion concept was numerically studied. The burner was designed for a 40 Nm^3/hr hydrogen-generated reformer using natural gas-steam reforming method. In order to satisfy the primary requirements for designing a reformer burner (uniform distribution of temperature along the fuel processor walls and minimum heat losses from the reformer), the features of the present burner configuration included 1) a self-regenerative burner for an exhaust-gas-recirculation to apply for the high-temperature air combustion concept, and 2) an annular-type shield for protecting direct contact of flame with the processor walls. For the injection velocities of the recirculated gas of 0.6-2.4 m/s, the recirculated gas temperature of 1000 K, and the recirculated oxygen mole fraction of 4%, the temperature distributions along the processor walls were found uniform within 100 K variation. Thus, the present burner configuration satisfied the requirement for reducing temperature gradients along the processor walls, and consequently demonstrated that the high-temperature air combustion concept could be applied to the practical fuel reformers for use of fuel cells. The uniformity of temperature distribution is enhanced as the amount of the recirculated gas increases.

주요기술용어 : High-Temperature Air Combustion(고온공기연소), Exhaust Gas Recirculation (배기재순환), Natural Gas/Steam Reforming(천연가스/증기 개질), Compact Reformer(컴팩트형 개질기), Fuel Cells(연료전지)

---

† Corresponding author : okwon@skku.edu

1. Introduction

Hydrogen is an attractive energy carrier, which is expected to replace fossil fuels in the near future, due to the clean and regenerative features. Fuel cells are considered as the primary applications of hydrogen use, e.g. for vehicle power production and for decentralized power generation[1]. Among the various methods, hydrogen product from renewable energy such as thermochemical, biological and photochemical water-splitting methods, promises well in the future; however, natural gas-steam reforming method has been widely used for hydrogen product due to the economy and the maturity of technology and seems to be continuously used in the near future, along with more recently developed auto-catalytic reforming and partial oxidation methods[2].

A natural gas-steam reforming system consists of a catalytic unit processor that converts fed natural gas and water steam into hydrogen (H_2) and carbon monoxide (CO) through an endothermic reaction, and a combustion system (burner) that provides the heat required for the catalytic processor. Thus, the development of inexpensive but still highly efficient catalysts has been considered the core step for developing a new reforming system. Recently, however, the importance of heat management in the system as well as development of new catalysts has been recognized[3]. In particular, it is important to realize that a highly efficient burner should be developed in that the core design technology of compact fuel reformers for use of small-capacity fuel cells is to minimize heat losses. There are two types of burners that are usually used: metal fiber burners and direct jet flame (gun-type) burners. The latter is advantageously used due to the economic merit; however, it causes large temperature gradients in the combustion chamber through which the catalytic processor passes. The large temperature gradients significantly degrade the performance of the fuel processor. Thus, a new burning method satisfying both the cost and the uniform heating of the processor should be developed.

Recently, a high-temperature air combustion (HTAC) concept[4] - in a combustion system, exhaust gas is recirculated and burned with fuel and fresh air (through a regenerative burner) so that the thermal efficiency improves due to heat recovery and simultaneously emissions of pollutant gases such as carbon dioxide (CO_2) and nitrogen oxide (NOx) decrease due to less fuel consumption and uniformly distributed temperature field - has been attempt to apply for industrial furnaces, and the applicability to the practical combustion systems was proven[5]. Among the features of the HTAC concept, the uniform-temperature distribution in the combustion system is expected to be most attractive if the concept is applied particularly for the natural gas-steam reforming burner. The direct jet flame burner applying for the HTAC concept could be one of the candidates for new burning methods satisfying both the cost and the uniform heating of the processor in the reformer burner.

Thus, the main objective of this investigation is to design a new high-performance burner for *a compact reformer* with the following specific objectives: 1) to determine a basic configuration of the burner for a 40 Nm^3/hr hydrogen-generated reformer; 2) to modify the basic configuration applying for the HTAC concept; and 3) to optimize the design through numerical simulations for various conditions.

The present discussion begins with descriptions of computational methods to design the burner. Results are then considered, treating a basic configuration and the optimized configuration applying for the HTAC concept.

2. Computational Methods

Commercially available CFD code FLUENT 6.0 was used to design a new configuration of the reformer burner[6]. The reacting flow in the combustion chamber was simulated with the continuity equation, the three-dimensional Navier-Stokes equations, the energy conservation equation and the species conservation equations. The turbulent flow and thermal radiation were modeled by the standard κ-ε model and the P-1 model, respectively[7]. Since the natural gas-steam reforming method was applied, methane (CH_4) was used for the burner fuel. A simple two-step irreversible CH_4/O_2 reaction mechanism involving five species CH_4, O_2, CO, CO_2 and H_2O was used[8], with eddy-dissipation model due to Magnussen and Hiertager[9] for the turbulent combustion. The eddy- dissipation model applied the concept that reaction rates influenced by turbulence are proportional to the dissipation rate and inversely proportional to the turbulent kinetic energy.

The governing equations adapting the above sub-models were discretized using non-staggered grid scheme, and solved by the SIMPLE algorithm for which every time step pressure is corrected[10]. The geometry (that will be discussed later) was a three-fold symmetric about the vertical axis; thus, computations were carried out for one-third part of the burner with 180,000 grids. The number of grids was determined through the grid-independence test varying the number 50,000 to 250,000, which showed no changes (within 1%) of the results beyond 150,000 grid points.

3. Results and Discussion

3.1 The Basic Burner Configuration

In the present study a burner configuration

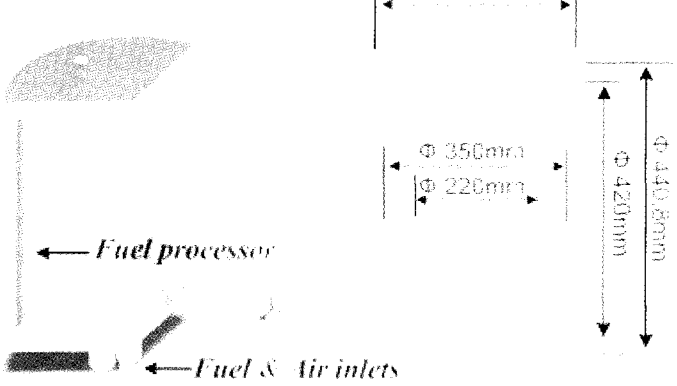

Fig. 1. Configuration of a basic burner.

Table 1. Dimensions of injection nozzles and injection conditions.

Parameters	Conditions
Diameter of fuel injection nozzle	4 mm
Diameter of air injection nozzle	8-32 mm (annular type)
Volume flow rate of fuel	62.8 cm^3/s
Volume flow rate of air	753.6 cm^3/s

for a 40 Nm^3/hr hydrogen- generated reformer was designed, since the production capacities of compact reformers of hydrogen stations being developed in Korea target 20-40 Nm^3/hr. Assuming that a commercial catalyst ICI 25-4/57-4 (NiO on a calcium aluminate) is used in the fuel processor, the size of the burner was determined.

In order to use a cheap but still uniformly heating direct jet flame burner rather than an expensive metal fiber burner, a cylindrical configuration was chosen as a basic geometry of the burner. The reason to keep temperature uniform around the fuel processor is that the large temperature gradients significantly degrade the performance of the fuel processor by the Boudouard reaction and the methane decomposition reaction that deposit carbon particles on the inner walls of the fuel processor[11]. In the practical purpose, it is known that the temperature difference along the outer walls of the fuel processor within 100 K is accepted. Due to this reason, several direct jet flame burners in a single combustion chamber are used to avoid peaks of temperature, if the direct flame heating method is applied. However, this approach is unacceptable for the compact-type reformers. Thus, the HTAC concept with the recirculation of exhaust gas using a regenerative burner was considered in this study. Figure 1 shows a basic burner configuration and major dimensions. The present design concerned only the burner configuration (not the whole reformer system), thus assuming the following conditions for the boundaries of the burner:

1) The catalytic processor was assumed to

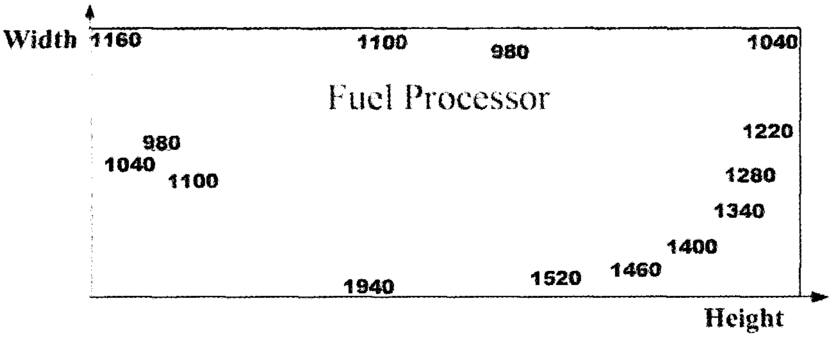

Fig. 2. Calculated temperature distribution for the basic burner.

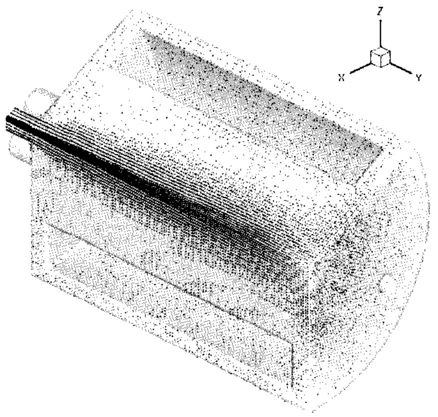

Fig. 3. Calculated velocity field for the basic burner.

be a dummy annular-type can into which the heat of 120 kW/m^2 transfers from the burner. The heat flux was chosen since the value usually shows the optimized hydrogen product performance for an endothermic reaction in the processor using ICI 25-4/57-4[12].

2) In order to minimize the heat loss from the burner, fresh air and the recirculated exhaust gas usually pass around the burner and then are fed into the nozzle; thus, considering this situation for the actual system, the heat loss on the outer walls of the burner is assumed 10W/m^2.

Prior to adopting the HTAC concept into the direct jet flame burner (shown in Fig. 1) using a regenerative burner, the temperature distribution in the basic burner was calculated and is shown in Fig. 2. Based on the repeated calculations considering the formed flame size, the heat transfer into the fuel processor and the thermal loads on the burner walls, the condition of fuel and air injection was determined as shown in Table 1. As shown in the figure, the direct heating the processor caused non-uniform heating due to the large temperature gradient. Also, the thermal loads concentrated into the top of the burner. Thus, as expected, the direct heating without regeneration is not suitable for the reformer burner application. The velocity field in the burner for the basic configuration is shown in Fig. 3.

3.2 The Optimized Burner Configuration Applying for the HTAC Concept

In order to apply the HTAC concept for the aforementioned basic burner, exhaust gas should be recirculated and regenerative burners should be used. For industrial furnaces, to which the applicability of the HTAC concept was proven, two or more burners were periodically and alternatively operated [4]. In the present compact reformer, however, the use of

Table 2. Dimensions of the self-regenerative burner injector.

Nozzle	Geometry	Number	Diameter (mm)
Fuel	Circular	1	4
Fresh air	Annular	1	8-32
Recirculated gas inlet	Circular	3	40
Exhaust outlet	Circular	3	40

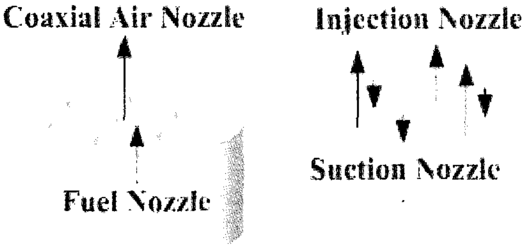

Fig. 4. A self-regenerative burner injector.

two or more burners causes the system to be incompact. Thus, in the present investigation, a self- regenerative burner in which exhaust nozzles and recirculated exhaust gas inlet nozzles are built was used[13]. Figure 4 shows the configuration of the burner injector, and the dimension is summarized in Table 2. The fuel nozzle in the center of the fresh air nozzle is surrounded by three the exhaust nozzles and three recirculated exhaust gas inlet nozzles.

An annular-type shield was installed between the injector and the fuel processor, in order to relieve significant temperature gradients near the fuel processor in addition to the HTAC concept, and in order to prevent direct contact of flame onto the walls of the processor. The final configuration of the burner considering all aspects so far is shown in Fig. 5, and computation grid points are indicated in Fig. 6.

The compositions and temperature of recirculated exhaust gas at inlet nozzles were estimated from those of the exhaust gas for the computations without the recirculation. All gases other than oxygen were assumed to be nitrogen for the compositions, whereas heat losses to surroundings were considered for temperature.

Figure 7 shows the temperature distribution in the final configuration of the burner, which was calculated for the conditions of Table 3. Compared to the temperature distribution without the recirculation of the exhaust (Fig. 2), the temperature distribution with the recirculation shows much less temperature gradients along the processor walls: basically uniform within 100 K. The velocity field in the

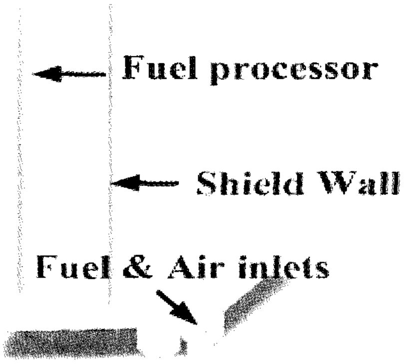

Fig 5. The final configuration of the burner.

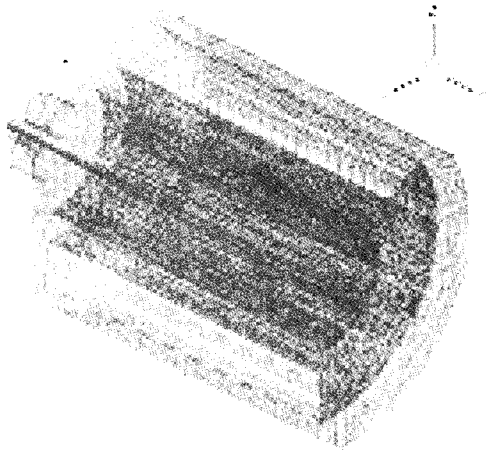

Fig. 6. Computational grids for the final configuration of the burner.

Table 3. Injection conditions for the final configuration of the burner.

Parameters	Conditions
Injection velocity of fuel	5 m/s
Injection velocity of air	1 m/s
Injection velocity of the recirculated gas	0.6 m/s
Compositions of the recirculated gas	4% O_2/96% N_2 in volume
Temperature of the recirculated gas	1000 K

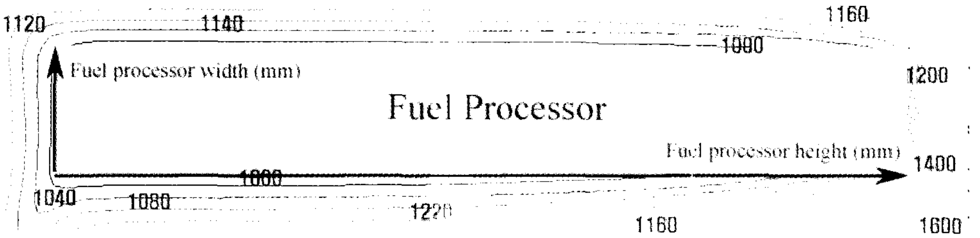

Fig. 7. Temperature distribution in the final configuration of the burner. (calculated for the condition of Table 3)

burner for the final configuration is shown in Fig. 8. In order to check the uniformity of temperature distribution due to the amount (injection velocity) of the recirculated gas, the cases for the injection velocities of 1.2 and 2.4 m/s were calculated and are shown in Figs. 9 and 10, respectively. As shown in the figures, the uniformity of temperature distribution is enhanced as the amount of the recirculated gas increases. This tendency is more clearly observed in Fig. 11, which shows the temperature profiles along the processor wall for the various injection amounts of the recirculated gas. The temperature distribution is acceptable for all the recirculated cases within 100 K variation between the ends of the part filled with catalyst in the fuel processor.

The present investigation showed a configuration design of the compact reformer burner. In order to find the optimized conditions for the present optimized configuration of the burner, some other aspects such as proper flame intensity should be considered in addition to the uniformity of the temperature distribution

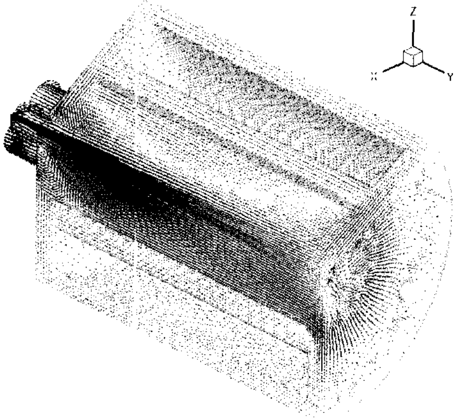

Fig. 8. Velocity field in the final configuration of the burner (calculated for the condition of Table 3)

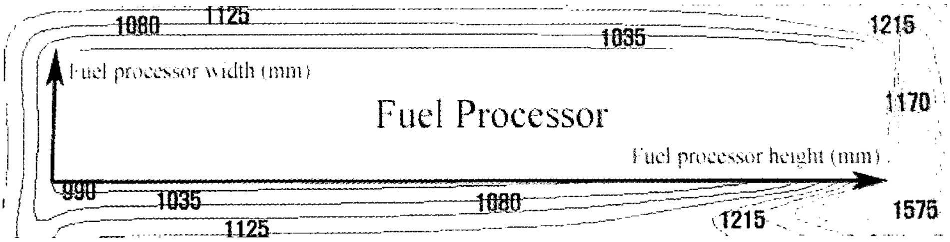

Fig. 9. Temperature distribution in the burner for enhanced injection amount of the recirculated gas: the injection velocity of the recirculated gas of 1.2 m/s.

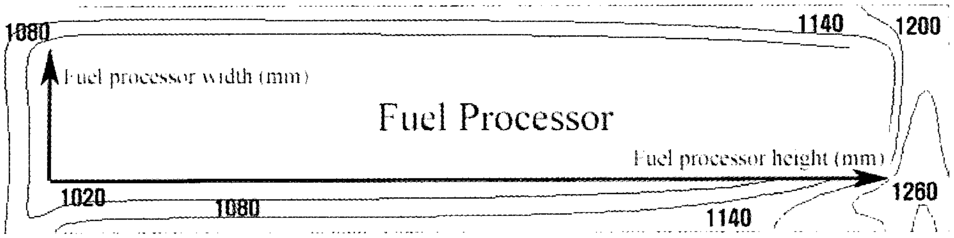

Fig. 10. Temperature distribution in the burner for enhanced injection amount of the recirculated gas: the injection velocity of the recirculated gas of 2.4 m/s.

along the processor walls. Also, the present numerical results should be experimentally demonstrated.

4. Conclusions

A new burner configuration for a compact fuel-cell reformer with a high- temperature air combustion concept was studied numerically. The burner was designed for a 40 Nm^3/hr hydrogen- generated reformer using natural gas- steam reforming method. The major conclusions of the study are as follows:

1. A self-regenerative burner applying for the HTAC concept was designed, in which the exhaust was recirculated. An annular-type shield was installed between the injector and the fuel processor in the burner, in order to relieve significant temperature gradients near the fuel processor and in order to prevent direct contact of flame onto the walls of the processor.
2. The uniformity of temperature along the

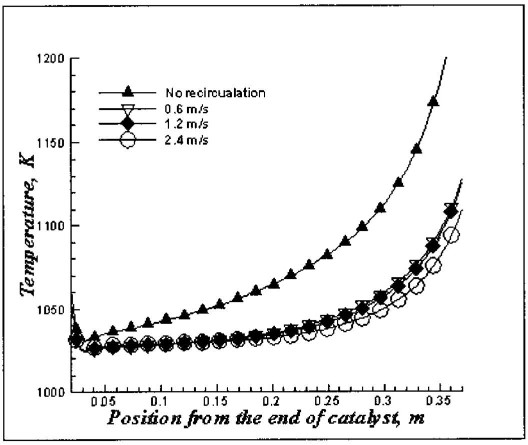

Fig. 11. Temperature profiles along the processor wall for the various injection amounts of the recirculated gas (the injection velocities of the recirculated gas of 0.6 to 2.4 m/s).

processor walls (the temperature difference between the ends of the part filled with catalyst in the fuel processor within 100 K) with the exhaust recirculation demonstrated successful application of the HTAC concept to the compact reformer burner for use of fuel cells, extending the applicability of the concept mainly from the industrial furnaces.

3. The uniformity of temperature distribution is enhanced as the amount of the recirculated gas increases.

Acknowledgements

This research was supported by Korea Research Foundation Grant (KRF-2004-003-D00044).

References

1) A. Lokurlu, T. Grube, B. Hohlein, and D. Stolten: "Fuel cells for mobile and stationary applications - cost analysis for combined heat and power stations on the basis of fuel cells", International Journal of Hydrogen Energy, Vol. 28, 2003, pp. 703-711.

2) J. N. Armor: "The Multiple Roles for Catalysis in the Production of H2", Applied Catalyst A: General, Vol. 176, No. 2, 1999, pp. 159-176.

3) W. L. Yoon and D. S. Seo: "Development of Compact NG steam Reforming System For H2-fueling Station" (in Korean), Workshop of Hydrogen Energy R&D Center, Vol.1, No.1, 2004, pp .3-7.

4) F. J. Weinberg: "Heat re-circulating burners: principles and some recent developments", Combustion Science and Technology, Vol. 121, 1996, pp. 3-22.

5) H. Tsuji, A. K. Gupta, T. Hasegawa, M. Katsuki, K. Kishimoto, and M. Morita: "High Temperature Air Combustion: from Energy Conservation to Pollution Reduction", CRC Press, New York, U.S.A., 2003, pp. 29-48.

6) Fluent Inc., Fluent 6.0 User's Guide, December 2001.

7) P. Cheng: "Two-Dimensional Radiating Gas Flow by a Moment Method", AIAA Journal, Vol. 2, 1964, pp. 1662-1664.

8) V. DuPont, M. Pourkashanian, and A. Williams: "Modeling of Process Heaters Fired by Natural Gas", Journal of Institute of Energy, Vol. 73, 1993, pp 20-29.

9) B. F. Magnussen and B. H. Hiertager: "On Mathematical Models of Turbulent Combustion with Species Emphasis on Soot Formation and Combustion", Proceedings of the Combustion Institute, Vol. 16, 1976, pp. 719-729.

10) J. P. Vandoormaal and G. D. Raithby: "Enhancements of the SIMPLE Method for Predicting Incompressible Fluid Flows", Numerical Heat Transfer, Vol. 7, 1984, pp. 147-163.

11) J. B. Claridge, A. P. E. York, A. J. Brungs, C. M. Alvarez, J. Sloan, S. C. Tsang, and M. L. H. Green: "New Catalysts for the Conversion of Methane to Synthesis Gas: Molybdenum and Tungsten Carbide", Journal of Catalysis, Vol. 180, 1998, pp. 85-100.

12) J. Pina, V. Bucala, and D. O. Borio: "Optimization of Steam Reformers: Heat Flux Distribution and Carbon Formation", International Journal of Chemical Reactor Engineering, Vol. 1, 2003, A25.

13) M. U. Kang: "A Study on Combustion Characteristics of the Self Regenerative Low NOx Burner", Master Degree Thesis, Seoul National University, Korea, 2003, pp. 4-10.