sCO2 연소기 수치 모사를 위한 실제-기체 기반 세 피드 스트림 화염편 모델

Danh Nam Nguyen, 이재훈, 유춘상†

A real-fluid based three-feed stream flamelet model for simulations of a simplified sCO2 combustor

Danh Nam Nguyen, Jae Hun Lee, Chun Sang Yoo†

Supercritical direct-fired CO_2 (sCO_2) cycle has been developed over the past several years as an innovatively affordable power generation technology that enables the world to meet its climate targets without pay more for electricity, while promising higher efficiencies with a smaller build. However, it is still challenging, and complicated in its component design due to not only the extremely high pressure in the operating conditions but also the highly diluted CO_2 injecting into the combustor at the order of 1000 K [1]. In the present paper we conduct the RANS simulations of a coaxial simplified sCO_2 gas turbine combustor proposed by Banuti et al. [2] using a newly developed real-fluid based framework with three-feed stream flamelet model. The purpose of this work is mainly for the validation of our developed platform.

The new platform is developed from the OpenFOAM-based real-fluid thermophysical library [3] and the work of Muller et al. [4]. In the development, a solver for two-feed stream problems referred as *2sRflameletFoam* which adopts the steady laminar flamelet model (SLFM) [5] and another solver for three-feed stream problems referred as *3sRflameletFoam* which adopts the SLFM with three-stream model [6,7] are created. These new solvers then are validated against the experimental data and previous studies. All numerical simulations conducted in the present work at high pressure employ the modified Soave-Redlich-Kwong (SRK) equation of state, the Chung model for dynamic viscosity and thermal conductivity and the Takahashi model for binary diffusion coefficients [8]. For the flamelet library preparation step, the one-dimensional (1-D) counterflow diffusion flames are generated by modified OPPDIF [9,10] in the physical space using the same set of real-fluid models as mentioned above. The flamelet solutions then are converted into mixture fraction space before being used in our newly developed OpenFOAM-based platform.

Since the implementation of real-fluid models in OpenFOAM has been validated until 300 atm and it can be used for any combustion solver in OpenFOAM utilizing the implemented models [3], we validate *2sRflameletFoam* solver by performing 2-D axisymmetric laminar counterflow non-premixed flame of CH_4 versus O_2/CO_2 at 200 atm as described in [3]. The result is presented in Fig. 1. It is shown that *2sRflameletFoam* can capture reasonably good flame profiles at high pressure using real-fluid based SLFM model compared to that of *realFluidReactingFoam* [3] excerpt for a small difference in the flame thickness as well as the maximum temperature which is mainly due to the unity Lewis number assumption applied in the flamelet model [5] while [3] adopted the detail transport.

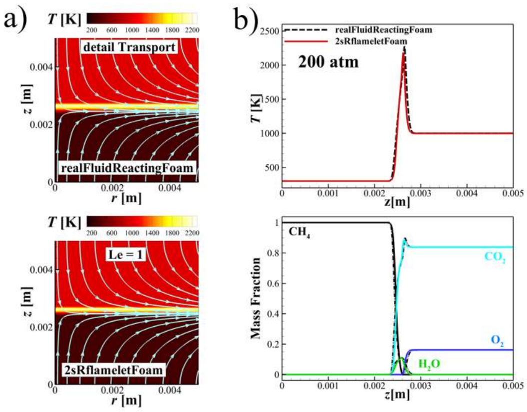

Figure 1. The comparison of the present study and benchmark data [3]: a) steady 2-D isocontour, b) 1-D profiles along the centerline

울산과학기술원 기계공학과
† 연락저자, csyoo@unist.ac.kr

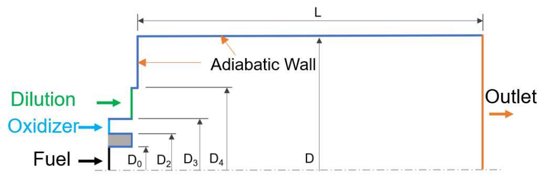

Figure 2. The schematic of coaxial simplified gas turbine combustor in the sCO_2 power cycles [2].

Figure 2 illustrates the schematic of a coaxial simplified sCO_2 gas turbine combustor [2] motivated from the rocket engine configuration but for the same flow rates and chamber diameter specified by Delimont et al. [1]. The detail geometry information is summarized in the table 1. The boundary conditions are mainly taken from the work of Delimont et al. [1] and Banuti et al. [2].

Table 1. Geometry of sCO_2 coaxial injector, dimensions in m [2].

D_0	D_2	D_3	D_4	D
0.003	0.005	0.007	0.0254	0.0508

It is of importance to note that if we set the dilution stream components involving CO_2 and O_2 as same as oxidizer stream instead of pure CO_2 both two-feed stream SLFM and three-feed stream SLFM model can be used for the coaxial simplified combustor configuration. We use this condition to validate *3sRflameletFoam* solver against *2sRflameletFoam* which has been validated as presented above. The results of RANS simulation of 2-D axisymmetric of the coaxial sCO_2 combustion at 200 atm are presented in Fig. 3. As expected, *3sRflameletFoam* can accurately predict the flame profiles relate to *2sRflameletFoam*. This implies that *3sRflameletFoam* solver is ready to be used for investigation of sCO_2 combustion.

Figure 4 shows the dilution effects in the coaxial simplified sCO_2 combustor through the distributions of the temperature, dilution factor (alpha) and CO_2 mass fraction. The more practical configurations of sCO_2 combustor will be investigated using the newly developed platform as our future works.

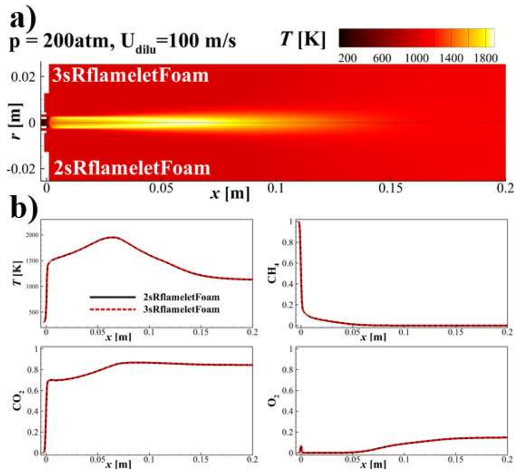

Figure 3. The validation of *3sRflameletFoam* solver: a) steady isocontour, b) 1D profiles along the centerline.

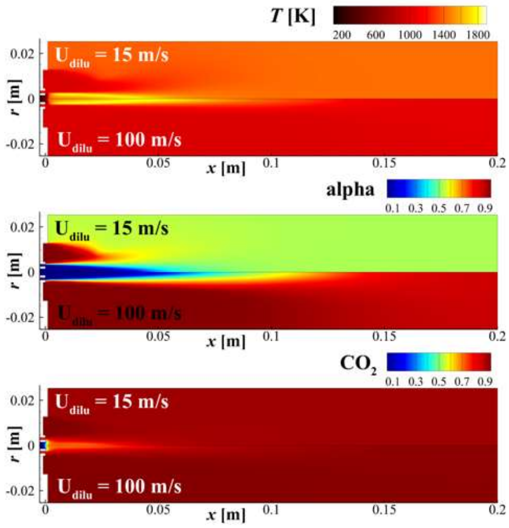

Figure 4. The distribution of temperature, dilution factor and CO_2 concentration at 200 atm using *3sRflameletFoam*.

Acknowledgement

This research was supported by Basic Science Research program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (NRF-2021R1A2C2005606).

References

[1] J. Delimont, N. Andrews, L. Chordia, 6th Int.

Symp. Sup. CO2 Power Cycles, 2018.
[2] D.T. Banuti, L. Shunn, S. Bose, D. Kim, 6th Int. Symp. Sup. CO2 Power Cycles, 2018.
[3] D.N. Nguyen, K.S. Jung, J.W. Shim, and C.S. Yoo, Comput. Phys. Commun., vol. 273, pp. 108264, 2022.
[4] H. Muller, F. Ferraro, M. Pfitzner, 8th Int. OpenFOAM Workshop, 2013.
[5] N. Peters, Prog. Energy Combust. Sci., vol. 10, pp. 319-339, 1984.
[6] M. Ihme and Y.C. See, Proc. Combust. Inst., vol. 33, pp. 1309-1317, 2011.
[7] G. Indelicato, P. Lapenna, R. Caputo, M. Valorani, G. Magnotti, F. Creta, Combust. Sci. Technol., vol. 192, pp. 2028-2049, 2020.
[8] G. Ribert, N. Zong, V. Yang, L. Pons, N. Darabiha, S. Candel, Combust. and Flame vol. 154 pp. 319–330, 2008.
[9] A. E. Lutz, R. J. Kee, J. F. Grcar, F. M. Rupley, "OPPDIF: A Fortran program for computing opposed-flow diffusion flames", United States.
[10] K.S. Jung, H.S. Bak, D.N. Nguyen, B.J. Lee, C.S. Yoo, Fuel, vol. 299, pp.120411, 2021.