PREDETONATION PROPERTIES OF ROTATING SUPERSONIC COMBUSTION ENGINE AT VARYING EQUIVALENCE RATIO

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ABSTRACT

Rotating detonation engine (RDE) is a new type of energy conversion system that utilizes detonation and has huge potential in replacing conventional combustion engines. However, to apply the RDE in real application, much work is still required especially in detonation initiation in both the predetonator and annulus chamber of RDE. A proper detonation reactant is crucial in an ignitor such as predetonator. Parameters affecting the formation of deflagration to detonation transition (DDT) in predetonator and predetonation behaviour on rotating wave initiation in RDE also remain unclear. Hence, this study aims to establish baseline fuel composition for predetonator by chemical equilibrium analysis. Calculations for ideal detonation characteristics in term of velocity, pressure, and temperature at varying equivalence ratio are performed using NASA-CEA software. The second aim of this study is to analyze the effects of equivalence ratio, the length of Shchelkin spiral, and the ignition energy in predetonator on DDT. Predetonation characterization that includes the measurement of velocity and pressure in predetonator were done to determine the effect of equivalence ratio, the length of Shchelkin spiral, and the ignition energy on DDT in the predetonator. The third aim for this study is to analyze the effects of predetonation exiting wave velocity to rotating detonation wave (RDW) initiation in RDE. In determining the effect of predetonation exiting wave velocity, characterization of RDW includes the measurement of period between predetonation and detonation and period of rotating detonation stabilization. Acetylene-oxygen (C_2H_2-O_2) results with the highest pressure ratio and temperature ratio thus is chosen as the reactant in the predetonator. Among the studied parameters, the impact of ignition energy is significant in the predetonator application. An average of 7.3% and 322% detonation velocity and pressure increments were obtained when ignition energy was increased from 50 mJ to 100 mJ. By increasing the predetonator exiting wave intensity, the reduction of the stabilisation period is achieved. The findings will guide further research into parameters that could create stable CRDW throughout the operation of RDE.

ABSTRAK

Enjin ledakan berputar (RDE) adalah sejenis sistem penukaran tenaga baru yang memanfaatkan ledakan dan mempunyai potensi yang besar dalam menggantikan enjin pembakaran konvensional. Walau bagaimanapun, untuk mengaplikasikan RDE dalam aplikasi sebenar, banyak usaha masih diperlukan terutamanya terhadap permulaan ledakan pada kedua-dua pranyalaan ledakan dan ruang anulus RDE. Bahan tindak balas ledakan yang betul adalah penting dalam pencucuh seperti pranyalaan ledakan. Parameter yang mempengaruhi pembentukan deflagrasi kepada peralihan ledakan (DDT) dalam pranyalaan ledakan dan tingkah laku praledakan pada permulaan gelombang berputar dalam RDE juga masih tidak jelas. Oleh itu, kajian ini bertujuan untuk mewujudkan komposisi bahan api asas untuk untuk pranyalaan ledakan melalui analisis keseimbangan bahan kimia. Pengiraan untuk ciri ledakan yang ideal dari segi halaju, tekanan, dan suhu pada nisbah kesetaraan yang berbeza-beza dilaksanakan menggunakan perisian NASA-CEA. Matlamat kedua kajian ini adalah untuk menganalisis kesan nisbah kesetaraan, panjang lingkaran Shchelkin, dan tenaga pencucuhan dalam pranyalaan ledakan pada DDT. Pencirian praledakan yang merangkumi pengukuran halaju dan tekanan dalam pranyalaan ledakan telah dilakukan untuk menentukan kesan nisbah kesetaraan, panjang lingkaran Shchelkin, dan tenaga pencucuhan pada DDT dalam pranyalaan ledakan. Matlamat ketiga untuk kajian ini adalah untuk menganalisis kesan kelajuan gelombang yang keluar dari pranyalaan ledakan kepada permulaan gelombang ledakan berputar (RDW) dalam RDE. Dalam menentukan kesan halaju gelombang yang keluar dari predetonator, pencirian RDW telah dibuat dengan mengambil kira pengukuran tempoh antara praledakan dan ledakan dan tempoh penstabilan ledakan berputar. Asetilena-oksigen (C_2H_2-O_2) menghasilkan nisbah tekanan dan nisbah suhu yang tertinggi maka dipilih sebagai bahan tindak balas di dalam pranyalaan ledakan. Antara parameter yang dikaji, impak tenaga pencucuhan adalah paling ketara dalam aplikasi pranyalaan ledakan. Kenaikan purata sebanyak 7.3% dan 322% pada halaju dan tekanan ledakan diperoleh apabila tenaga pencucuhan ditingkatkan daripada 50 mJ kepada 100 mJ. Dengan meningkatkan intensiti gelombang keluar dari pranyalaan ledakan, pengurangan tempoh penstabilan dicapai. Penemuan ini akan membimbing penyelidikan lanjut terhadap parameter yang boleh mewujudkan CRDW yang stabil sepanjang operasi RDE.

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LIST OF ABBREVIATIONS

UTM - Universiti Teknologi Malaysia
HiREF - High Speed Reacting Flow
RDE - rotating detonation engine
CRDE - continuous rotating detonation engine
DDT - deflagration to detonation transition
RDW - rotating detonation wave
CRDW - continuous rotating detonation wave

LIST OF SYMBOLS

% - percentage

deg - degree

C_2H_2 - acetylene

O_2 - oxygen

H_2 - hydrogen

CH_4 - methane

C_2H_2-O_2 - acetylene-oxygen

H_2-O_2 - hydrogen-oxygen

CH_4-O_2 - methane-oxygen

t_d - time of first detonation

t_p - time of predetonation

t_{ds} - time of first stable detonation

$t_d - t_p$ - period between predotanation and detonation

$t_{ds} - t_d$ - period of rotating detonation stabilization

CHAPTER 1

INTRODUCTION

1.1 Background

In today's dwindling fuel resources, great stress has been given on sustainability and improvement in efficiency. As to assist in achieving the aim, government and industry has shifted their focus towards finding ways to cut back in fuel consumption. This increases the motivation of researchers in seeking of new technologies that is more efficient with lower emission production [8] and lower fuel consumption [9]. Through these efforts, rotating detonation engine (RDE) is one of the innovative solution developed with promising advantages compared to the conventional gas turbine engine. RDE is a revolutionary technology in industrial turbine generators as well in aircraft and aerospace propulsion that guarantees vital in fuel saving and reduction in exhaust pollutants. The main difference between RDE and the conventional gas turbine engine is the mode of combustion used which is detonation and deflagration respectively.

What interests researchers involve in the field of power and propulsion studies are, the application of detonation by RDE which has many advantages. The current gas turbine systems utilise deflagration mode to burn the reactant mixture. The deflagration mode requires multi-stages compressors to elevate the pressure prior to being burned in a combustor. On the other hand, detonation mode of combustion release energy more rapidly and has higher thermal efficiency compared to deflagration mode [10]. With pressure gain attribute in detonation phenomenon, it can minimise the pressure that is required to compress the incoming air in the gas turbine system, thus, contribute to less compressor stages as compared to the conventional gas turbine systems. With less compressor stages, the structure of RDE could be kept simple and compact.

RDEs have the potential also to be integrated into all gas turbine systems used in the aircraft, aerospace and land power generation industries. The RDE concept represents the next-generation of energy conversion system because it provides higher performance and close to constant thrust with a less complicated overall design. To accomplish this aim, the creation of a dependable and functional RDE system powered by stable and continuous thrust are required. Thus, this research aims to improved the rotating detonation wave (RDW) initiation by implementing different type of exiting wave produce by the predetonator.

1.2 Problem Statement

Much work has been carried out in High Speed Reactive Flow (HiREF) laboratory located in Universiti Teknologi Malaysia (UTM) to implement rotating detonation engine (RDE) in real application. These work have been distributed to all the components of RDE. Among the components in RDE, ignition system is one of the important component. The ignition of fuel-oxidizer mixture in RDE with sufficient energy is a very important element in initiating a successful supersonic detonation. In fact, the ignition with subsequent transition from deflagration to steady detonation operation is a key factor for the successful development of RDE. In HiREF, predetonator has been used as an initiator for the RDE. Predetonator is commonly used in RDE studies to start rotating detonation waves (RDWs). Predetonator emits a combustion wave into the annulus chamber of to ignite RDWs. The problem is, the formation of detonation may occur either in the annulus chamber of the RDE if not in the predetonator. This leads to the requirement of a suitable mixture to be used in the predetonator. Few detonation reactant composition studies have been done on hydrogen-oxygen [11], acetylene-oxygen [12], and methane-oxygen [13], but systematic comparison of detonation reactant composition based on chemical equilibrium analysis between the mixtures is very limited. Although formation of detonation may occur in the annulus chamber, there are some concerns about the effectiveness of maintaining the rotating detonation wave. RDWs tends to decay after formation of counter waves if detonation is form in the annulus chamber of RDE. Therefore, the control of formation of detonation in the predetonator could potentially provide better RDE initiation. To control detonation formation in the predetonator, the understanding of deflagration to detonation transition (DDT) phenomena in small channel is required. Few studies on detonation formation in predetonator have been done [14, 15], but the effects of equivalence ratio, length of shchelkin spiral, and ignition energy on DDT in predetonator still remain unclear. If detonation was to be successfully ignited in the predetonator, the effect of predetonation behaviour on rotating wave initiation in RDE still remain unclear [16]. So, the purpose of this research is to analyze the effects of predetonation exiting wave velocity to (RDE) initiation.

1.3 Research Objectives

The main objectives of the present study are as followed:

(a) To establish baseline fuel composition for predetonator by chemical equilibrium analysis.

(b) To analyze the effects of equivalence ratio, the length of Shchelkin spiral, and the ignition energy in predetonator on the deflagration to detonation transition (DDT).

(c) To analyze the effects of predetonation exiting wave velocity to rotating detonation engine (RDE) initiation.

1.4 Scope of Research

The scope of the present study are as followed:

(a) This research was done with the combination of both chemical equilibrium analysis and experiment.

(b) For objective (a), chemical equilibrium analysis are done for mixtures of acetylene-oxygen (C_2H_2-O_2), hydrogen-oxygen (H_2-O_2), and methane-oxygen (CH_4-O_2) at varying equivalence ratios, range from 0.7 to 3.0.

(c) For objective (b), experiment was done invloving predetonator. The parameters used in the predetonation characterization study are equivalence ratio (0.7 to

1.3), ignition energy (50 mJ and 100 mJ), and shchelkin spiral length (0 mm, 30 mm, 60 mm, 90 mm).

(d) For objective (c), experiment was done with combination of both predetonator and RDE.

(e) The geometry of RDE was based on the previous study done in HiREF UTM.

(f) The reactant used in the predetonator and RDE are C_2H_2-O_2 and CH_4-O_2 respectively.

(g) The current study focus only on the propagating wave close to predetonator exit and on the RDWs initiation in the RDE.

REFERENCES

1. Wolanski, P. Detonation Engines. *Journal of KONES Powertrain and Transport*, 2011. 18(3): 515–521.

2. Zhou, R., Wu, D. and Wang, J. Progress of continuously rotating detonation engines. *Chinese Journal of Aeronautics*, 2016. 29(1): 15–29.

3. Kellenberger, M. and Ciccarelli, G. Simultaneous schlieren photography and soot foil in the study of detonation phenomena. *Experiments in Fluids*, 2017. 58(10): 1–13.

4. Liu, S. J., Lin, Z. Y., Liu, W. D., Lin, W. and Sun, M. B. Experimental and three-dimensional numerical investigations on H2/air continuous rotating detonation wave. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2013. 227(2): 326–341.

5. Ma, Z., Zhang, S., Luan, M., Yao, S., Xia, Z. and Wang, J. Experimental research on ignition, quenching, reinitiation and the stabilization process in rotating detonation engine. *International Journal of Hydrogen Energy*, 2018. 43(39): 18521–18529.

6. Shank, J. C., King, P. I., Karnesky, J., Schauer, F. R. and Hoke, J. L. Development and Testing of a Modular Rotating Detonation Engine. *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2012. (January): 1–10.

7. Miller, S., King, P., Schauer, F. and Hoke, J. Ignition Design For a Rotating Detonation Engine. *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2013. (January): 1–11.

8. Buhre, B. J., Elliott, L. K., Sheng, C. D., Gupta, R. P. and Wall, T. F. Oxy-fuel combustion technology for coal-fired power generation. *Progress in Energy and Combustion Science*, 2005. 31(4): 283–307.

9. Sousa, J., Paniagua, G. and Collado Morata, E. Thermodynamic analysis of a gas turbine engine with a rotating detonation combustor. *Applied Energy*, 2017. 195: 247–256.

10. Zhou, S., Ma, H., Ma, Y., Zhou, C., Liu, D. and Li, S. Experimental study on a rotating detonation combustor with an axial-flow turbine. *Acta Astronautica*, 2018. 151(March): 7–14.

11. Metrow, C., Gray, S. and Ciccarelli, G. Detonation propagation through a nonuniform layer of hydrogen-oxygen in a narrow channel. *International Journal of Hydrogen Energy*, 2021. 46(41): 21726–21738.

12. Yang, T., Ning, J. and Li, J. Propagation mechanism of gaseous detonations in annular channels with spiral for acetylene-oxygen mixtures. *Fuel*, 2021. 290: 119763.

13. Nair, A. P., Lee, D. D., Pineda, D. I., Kriesel, J., Hargus Jr, W. A., Bennewitz, J. W., Bigler, B., Danczyk, S. A. and Spearrin, R. M. Methane-oxygen rotating detonation exhaust thermodynamics with variable mixing, equivalence ratio, and mass flux. *Aerospace Science and Technology*, 2021. 113: 106683.

14. Xia, Z.-J., Sheng, Z.-H., Shen, D.-W. and Wang, J.-P. Numerical investigation of pre-detonator in rotating detonation engine. *International Journal of Hydrogen Energy*, 2021. 46(61): 31428–31438.

15. Fiorino, N. T., Schauer, F. R., Polanka, M. D., Schumaker, S. A. and Sell, B. C. Use of a Partially Pre-Mixed Injection Scheme and Pre-Detonator in a Small Scale Rotating Detonation Engine. *AIAA Propulsion and Energy 2021 Forum*. 2021. 3656.

16. Xia, Z., Ma, H., Ge, G. and Zhou, C. Effects of ignition condition on the initiation characteristics of rotating detonation wave in plane-radial structure. *Acta Astronautica*, 2020. 175: 79–89.

17. Saracoglu, B. H. and Ozden, A. The effects of multiple detonation waves in the RDE flow field. *Transportation Research Procedia*, 2018. 29: 390–400.

18. Zhou, S., Ma, H., Ma, Y., Zhou, C., Liu, D. and Li, S. Experimental study on a rotating detonation combustor with an axial-flow turbine. *Acta Astronautica*, 2018. 151: 7–14.

19. Brent, T. Evaluation and selection of an efficient fuel/air initiation strategy for pulse detonation engine. 2005.

20. Nordeen, C. *Thermodynamics of a Rotating Detonation Engine*. Ph.D. Thesis. 2013.

21. Vizcaino, J. Investigation of Pulse Detonation Engines ; Theory , Design and Analysis. 2013.

22. Huang, J., Han, W., Gao, X. and Wang, C. Effects of heat loss and viscosity friction at walls on flame acceleration and deflagration to detonation transition. *Chinese Physics B*, 2019. 28(7): 074704.

23. Heister, S. D. and Stechmann, D. P. Survey of Rotating Detonation Wave Combustor Technology and Potential Rocket Vehicle Applications. *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 2014: 1–11.

24. Falempin, F. Continuous Detonation Wave Engine. *Advances on Propulsion Technology for High-Speed Aircraft*, 2008. RTO-EN-AVT: 8.1–8.16.

25. Lu, F. K., Carter, J. D. and Wilson, D. R. Pulse Detonation Engine Demonstrator. *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 2011. (August): 1–15.

26. Lu, F. K. and Braun, E. M. Rotating Detonation Wave Propulsion: Experimental Challenges, Modeling, and Engine Concepts. *Journal of Propulsion and Power*, 2014. 30(5): 1125–1142. URL `http://arc.aiaa.org/-doi/10.2514/1.B34802`.

27. Yao, S., Ma, Z., Zhang, S., Luan, M. and Wang, J. Reinitiation phenomenon in hydrogen-air rotating detonation engine. *International Journal of Hydrogen Energy*, 2017. 42(47): 28588–28598.

28. Rankin, B. A., Richardson, D. R., Caswell, A. W., Naples, A. G., Hoke, J. L. and Schauer, F. R. Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine. *Combustion and Flame*, 2017. 176: 12–22.

29. Sheriff, Z., Ilavarasi, M. and Niranjana, K. Performance optimization of pulse detonation Engine. *International Conference on Recent Advances in Aerospace Engineering*, 2017.

30. Kiyanda, C. B., Connolly-boutin, S., Joseph, V., Mi, X., Ng, H. D. and Higgins, A. J. Small Size Rotating Detonation Engine : Scaling and Minimum Mass Flow Rate. *26th ICDERS*, 2017: 1–6.

31. Wang, J. P., Liu, Y. F. and Li, T. W. Numerical studies of pre-detonator ignition of pulse detonation engine. 2005: 1–6.

32. Roy, G. D., Frolov, S. M., Borisov, A. A. and Netzer, D. W. Pulse detonation propulsion: Challenges, current status, and future perspective. *Progress in Energy and Combustion Science*, 2004. 30(6): 545–672.

33. Frolov, S. M., Aksenov, V. S., Ivanov, V. S. and Shamshin, I. O. Large-scale hydrogen-air continuous detonation combustor. *International Journal of Hydrogen Energy*, 2015. 40(3): 1616–1623.

34. St. George, A. C., Driscoll, R. B., Munday, D. E. and Gutmark, E. J. Development of a Rotating Detonation Engine Facility at the University of Cincinnati. *53rd AIAA Aerospace Sciences Meeting*, 2015. (January): 1–12.

35. Shank, J. C. Development and testing of a rotating detonation engine run on hydrogen and air. *Using Multiple Objective Decision Analysis to Position Federal Product and Service Codes Within the Kraljic Portfolio matrix*, 2015.

36. Russo, R. M. Operational Characteristics of a Rotating Detonation Engine Using Hydrogen and Air. 2011.

37. Eyl, D., Ve, S. and Tez, S. operational space and characterization of a rotating detonation engine using hydrogen and air. 2012.

38. Anand, V., St. George, A. C. and Gutmark, E. J. Hollow Rotating Detonation Combustor. *54th AIAA Aerospace Sciences Meeting*, 2016. (January): 1–15. URL `http://arc.aiaa.org/-doi/10.2514/6.2016-0124`.

39. Paxson, D. E., Fotia, M., Hoke, J. and Schauer, F. Comparison of Numerically Simulated and Experimentally Measured Performance of a Rotating Detonation Engine. *53rd AIAA Aerospace Sciences Meeting*, 2015. (August 2015). URL `http://arc.aiaa.org/-doi/10.2514/6.2015-1101`.

40. Boening, J. A. Initiation of Orderly Spinning Detonation Waves via Phased Sparking. 2016.

41. Driscoll, R. B. Investigation of Sustained Detonation Devices: the Pulse Detonation Engine-Crossover System and the Rotating Detonation Engine System. 2016: 219.

42. Valli, D. M. and Jindal, T. K. Pulse Detonation Engine : Parameters. 2014. 3(4): 11229–11237.

43. Wen, C., Chung, K., Hsu, Y. and Lu, F. Smoked Foil on Deflagration-to-Detonation Transition. *Journal of Propulsion and Power*, 2015. 31(3): 967–970.

44. Yang, C., Wu, X., Ma, H., Peng, L. and Gao, J. Experimental research on initiation characteristics of a rotating detonation engine. *Experimental Thermal and Fluid Science*, 2016. 71: 154–163.

45. Schultz, E., Wintenberger, E. and Shepherd, J. *Investigation of Deflagration to Detonation Transition for Application to Pulse Detonation Engine Ignition Systems*. Technical report. 1999.

46. Wang, Z., Yan, C., Zheng, L. and Fan, W. Experimental study of ignition and detonation initiation in two-phase valveless pulse detonation engines. *Combustion Science and Technology*, 2009. 181(10): 1310–1325.

47. Matsukov, M. K. V. A. I. DDT in a smooth tube filled with a hydrogen – oxygen mixture. *Shock Waves*, 2005. 14: 205–215.

48. Turns, S. R. *et al.* *Introduction to combustion*. vol. 287. McGraw-Hill Companies New York, NY, USA. 1996.

49. Glassman, I., Yetter, R. A. and Glumac, N. G. *Combustion*. Academic press. 2014. ISBN 0124115551.

50. Lee, S. H., Jo, D. R. and Choi, J. Y. Effect of curvature on the detonation wave propagation characteristics in annular channels. *46th AIAA Aerospace Sciences Meeting and Exhibit*, 2008. (January): 1–9.

51. Agrawal, J. P. *High energy materials: propellants, explosives and pyrotechnics*. John Wiley & Sons. 2010.

52. hailong Zhang, Liu, W. and Liu, S. Effects of inner cylinder length on H2_air rotating detonation. *international journal of hydrogen*, 2016. 41.

53. Denisov, Y. N. Pulsating and spinning detonation of gaseous mixtures in tubes. *Dokl. Akad. Nauk SSSR*. 1959, vol. 125. 110–113.

54. Coates, A. M., Mathias, D. L. and Cantwell, B. J. Numerical investigation of the effect of obstacle shape on deflagration to detonation transition in a hydrogen–air mixture. *Combustion and Flame*, 2019. 209: 278–290.

55. Canteins, G. and Canteins, G. Etude de la détonation continue rotative - Application à la propulsion To cite this version : HAL Id : tel-00124803 Thèse Etude de la détonation continue rotative - Application à la propulsion -. 2007.

56. Thomas, L., Schauer, F., Hoke, J. and Naples, A. Buildup and Operation of a Rotating Detonation Engine. *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2011. (January): 1–10.

57. Liu, S.-j., Lin, Z.-y., Liu, W.-d., Lin, W., Zhuang, F.-c., Lin, Z.-y., Liu, W.-d., Lin, W. and Zhuang, F.-c. Experimental Realization of H 2 / Air Continuous Rotating Detonation in a Cylindrical Combustor. 2012. 2202.

58. Dyer, R. Parametric Testing of a Unique Rotating Detonation Engine Design. 2012. (January): 1–8.

59. Oran, E. S. and Gamezo, V. N. Origins of the deflagration-to-detonation transition in gas-phase combustion. *Combustion and flame*, 2007. 148(1-2): 4–47.

60. Wang, C., Huang, F., Addai, E. K. and Dong, X. Effect of concentration and obstacles on flame velocity and overpressure of methane-air mixture. *Journal of Loss Prevention in the Process Industries*, 2016. 43: 302–310.

61. Qin, Y. and Chen, X. Flame propagation of premixed hydrogen-air explosion in a closed duct with obstacles. *International Journal of Hydrogen Energy*, 2021. 46(2): 2684–2701.

62. Goodwin, G. B., Houim, R. W. and Oran, E. S. Effect of decreasing blockage ratio on DDT in small channels with obstacles. *Combustion and Flame*, 2016. 173: 16–26.

63. Kindracki, J., Wolanski, P. and Gut, Z. Experimental research on the rotationg detonation in gaseous fuel-oxygen mixture. 2011: 75–84.

64. Guirao, C. M., Knystautas, R. and Lee, J. H. *A Summary of Hydrogen-Air Detonation Experiments*. Technical report. 1989.

65. Wang, L. Q., Ma, H. H. and Shen, Z. W. Effect of orifice plates on detonation propagation in stoichiometric hydrogen-oxygen mixture. *Experimental Thermal and Fluid Science*, 2018. 99(February): 367–373.

66. Lentsch, A., Bec, R., Piton, D. and Prigent, A. Overview of Current French Activities on PDRE and Continuous Detonation Wave Rocket Engines. 2005: 1–13.

67. Oppenheim, A. K. Dynamics of combustion systems. 2008.

68. Zhong, Y., Jin, D., Wu, Y. and Chen, X. Investigation of rotating detonation wave fueled by "ethylene-acetylene-hydrogen" mixture. *International Journal of Hydrogen Energy*, 2018. 43(31): 14787–14797.

69. Smirnov, N. N., Betelin, V. B., Nikitin, V. F., Phylippov, Y. G. and Koo, J. Detonation engine fed by acetylene-oxygen mixture. *Acta Astronautica*, 2014. 104(1): 134–146. URL `http://dx.-doi.org/10.1016/j.actaastro.2014.07.019`.

70. Zhang, F. *Shock Waves Science and Technology Library, Vol. 6: Detonation Dynamics*. vol. 6. Springer Science & Business Media. 2012.

71. Zheng, H., Meng, Q., Zhao, N., Li, Z. and Deng, F. Numerical investigation on H2/Air non-premixed rotating detonation engine under different equivalence ratios. *International Journal of Hydrogen Energy*, 2020. 45(3): 2289–2307.

72. Teng, H., Zhou, L., Yang, P. and Jiang, Z. Numerical investigation of wavelet features in rotating detonations with a two-step induction-reaction model. *International Journal of Hydrogen Energy*, 2020. 45(7): 4991–5001.

73. Zhang, B., Liu, H., Yan, B. and Ng, H. D. Experimental study of detonation limits in methane-oxygen mixtures: Determining tube scale and initial pressure effects. *Fuel*, 2020. 259: 116220.

74. Deng, L., Ma, H., Xu, C., Zhou, C. and Liu, X. Investigation on the propagation process of rotating detonation wave. *Acta astronautica*, 2017. 139: 278–287.

75. Li, B., Wu, Y., Weng, C., Zheng, Q. and Wei, W. Influence of equivalence ratio on the propagation characteristics of rotating detonation wave. *Experimental thermal and fluid science*, 2018. 93: 366–378.

76. Wang, Z., Wang, K., Li, Q., Zhu, Y., Zhao, M. and Fan, W. Effects of the combustor width on propagation characteristics of rotating detonation waves. *Aerospace Science and Technology*, 2020. 105: 106038.

77. Zheng, Q., Meng, H.-l., Weng, C.-s., Wu, Y.-w., Feng, W.-k. and Wu, M.-l. Experimental research on the instability propagation characteristics of liquid kerosene rotating detonation wave. *Defence Technology*, 2020. 16(6): 1106–1115.

78. Peng, H.-Y., Liu, W.-D., Liu, S.-J., Zhang, H.-L. and Jiang, L.-X. Hydrogen-air, ethylene-air, and methane-air continuous rotating detonation in the hollow chamber. *Energy*, 2020. 211: 118598.

79. Ma, J. Z., Zhang, S., Luan, M. and Wang, J. Experimental investigation on delay time phenomenon in rotating detonation engine. *Aerospace Science and Technology*, 2019. 88: 395–404.

80. Zhang, B., Liu, H. and Wang, C. On the detonation propagation behavior in hydrogen-oxygen mixture under the effect of spiral obstacles. *International Journal of Hydrogen Energy*, 2017. 42(33): 21392–21402. URL `http://dx.-doi.org/10.1016/j.ijhydene.2017.06.201`.

81. Goodwin, G. B., Houim, R. W. and Oran, E. S. Shock transition to detonation in channels with obstacles. *Proceedings of the Combustion Institute*, 2017. 36(2): 2717–2724. URL `http://dx.-doi.org/10.1016/j.proci.2016.06.160`.

82. Anand, V., George, A. S. and Gutmark, E. Amplitude modulated instability in reactants plenum of a rotating detonation combustor. *International Journal of Hydrogen Energy*, 2017. 42(17): 12629–12644.

83. Radulescu, M. and Hanson, R. Effect of heat loss on pulse-detonation-engine flow fields and performance. *Journal of Propulsion and Power*, 2005. 21(2): 274–285.

84. Zhang, B., Liu, H. and Wang, C. On the detonation propagation behavior in hydrogen-oxygen mixture under the effect of spiral obstacles. *International Journal of Hydrogen Energy*, 2017. 42(33): 21392–21402.

85. Wang, Y., Le, J., Wang, C. and Zheng, Y. A non-premixed rotating detonation engine using ethylene and air. *Applied Thermal Engineering*, 2018. 137(April): 749–757. URL `https://-doi.org/10.1016/j.applthermaleng.2018.04.015`.

86. Peng, H., Liu, W., Liu, S. and Zhang, H. Experimental investigations on ethylene-air Continuous Rotating Detonation wave in the hollow chamber with Laval nozzle. *Acta Astronautica*, 2018. 151: 137–145.

87. Zhou, S., Ma, H., Chen, S., Zhong, Y. and Zhou, C. Experimental investigation on propagation characteristics of rotating detonation wave with a hydrogen-ethylene-acetylene fuel. *Acta Astronautica*, 2019. 157: 310–320.

88. Sun, J., Zhou, J., Liu, S., Lin, Z. and Lin, W. Effects of air injection throat width on a non-premixed rotating detonation engine. *Acta Astronautica*, 2019. 159: 189–198.

89. Xia, Z., Ma, H., Liu, C., Zhuo, C. and Zhou, C. Experimental investigation on the propagation mode of rotating detonation wave in plane-radial combustor. *Experimental Thermal and Fluid Science*, 2019. 103: 364–376.

90. Peng, H.-y., Liu, W.-D., Liu, S.-j. and Zhang, H.-l. The effect of cavity on ethylene-air continuous rotating detonation in the annular combustor. *international journal of hydrogen energy*, 2019. 44(26): 14032–14043.

LIST OF PUBLICATIONS

Indexed Journal (SCOPUS)

1. Title: Initiation Characteristics of Rotating Supersonic Combustion Engine
   Authors: Muhammad Amri Mazlan, Mohd Fairus Mohd Yasin, Aminuddin Saat, Mazlan Abdul Wahid, Ahmad Dairobi Ghazali, Mohammad Nurizat Rahman
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