- Published: 18 December 2019

Chemical, thermal and dilution effects of carbon dioxide in oxy-fuel combustion of wood in a fixed bed

- Josephat Kipyegon Tanui[1],
- Paul Ndirangu Kioni[1],
- Thomas Mirre[2] &
- [...]
- Mario Nowitzki[2]
- - Show fewer authors

Journal of Mechanical Science and Technology **volume 33**, pages6063–6073(2019)Cite this article

Abstract

Experimental and numerical modeling was performed on eucalyptus wood combustion under oxy-fuel conditions using a fixed bed reactor in order to isolate the role of various carbon dioxide effects on the burning rate. Wood combustion was investigated under four different mixtures of O_2 and Ar/CO_2/N_2: 21 % O_2/79 % N_2; 21 % O_2/22.5 % CO_2/56.5 % Ar; 40 % O_2/60 % CO_2; and 40 % O_2/47 % CO_2/13 % Ar. The first three mixtures were designed to have the same peak temperatures in order to isolate chemical and dilution effects of CO$_2$ was achieved by substituting some percentage of CO_2 with Ar in O_2/CO_2 mixture while maintaining a constant

concentration of O_2. The fourth mixture was meant to isolate the thermal effect of CO_2. The results were obtained from both the experimental rig and numerical simulation for a fixed bed configuration. Wood combustion in the fixed bed was modeled using Lagrange-Euler method, where gas-phase was calculated using computational fluid dynamics (CFD), that is Euler phase, while solid-phase was tracked in Lagrange phase using discrete element method (DEM). The results show that ignition time in CO_2 environment decreases gradually as O_2 concentration is increased. On the other hand, burning rate and flame front speed increase as O_2 concentration is increased. It was established that dilution effect is the most influential parameter on the burning rate of wood combustion in an oxy-fuel system.

References

1. [1]

   International Energy Agency, *World Energy Outlook 2016: Executive Summary*, https://www.iea.org (2016).

   - Google Scholar

2. [2]

   S. K. Hong, D. S. Noh and J. B. Yang, Experimental study of honeycomb regenerator system for oxy-fuel combustion, *J. of Mechanical Science and Technology*, 27 (4) (2013) 1151–1154.

   - Article
   - Google Scholar

3. [3]

   S. H. Tak, S. K. Park, T. S. Kim, J. L. Sohn and Y. D. Lee, Performance analyses of oxy-fuel power generation systems including CO_2 capture: Comparison of two cycles using different recirculation fluids, *J. of Mechanical Science and Technology*, 24 (9) (2010) 1947–1954.

   - Article
   - Google Scholar

4. [4]

D. Kim and S. Choi, Effect of typical modeling assumptions for pulverized coal char combustion commonly used in commercial CFD codes, *J. of Mechanical Science and Technology*, 29 (11) (2015) 4951–4961.

- Article
- Google Scholar

5. [5]

R. Ben-Mansour, P. Ahmed, M. A. Habib and A. Jamal, Oxy-combustion of liquid fuel in an ion transport membrane reactor, *International J. of Energy and Environmental Engineering*, 9 (2018) 21–37.

- Article
- Google Scholar

6. [6]

R. Marsh, J. Runyon, A. Giles, S. Morris, D. Pugh, A. Valera-Medina and P. Bowen, Premixed methane oxycombustion in nitrogen and carbon dioxide atmospheres: Measurement of operating limits, flame location and emissions, *Proceedings of the Combustion Institute*, 36 (3) (2017) 3949–3958.

- Article
- Google Scholar

7. [7]

G. Scheffknecht, L. Al-Makhadmeh, U. Schnell and J. Maier, Oxy-fuel coal combustion — A review of the current state-of-the-art, *International J. of Greenhouse Gas Control*, 5 (2011) 16–35.

- Article
- Google Scholar

8. [8]

J. Ahn, H. J. Kim and K. S. Choi, Oxy-fuel combustion boiler for CO_2 capturing: 50 kW-class model test and numerical simulation, *J. of Mechanical Science and Technology*, 24 (10) (2010) 2135–2141.

- Article
- Google Scholar

9. [9]

S. K. Hong, K. G. Kang, D. S. Noh, E. K. Lee and H. S. Ryou, Development of an oxy-fuel combustor with fuel preheating for regenerator system, *J. of Mechanical Science and Technology*, 29 (10) (2015) 4555–4559.

- Article
- Google Scholar

10. [10]

S. Park, J. A. Kim, C. Ryu, W. Yang, Y. J. Kim and S. Seo, Effects of gas and particle emissions on wall radiative heat flux in oxy-fuel combustion, *J. of Mechanical Science and Technology*, 26 (5) (2012) 1633–1641.

- Article
- Google Scholar

11. [11]

A. Molina and C. R. Shaddix, Ignition and devolatilization of pulverized bituminous coal particles oxygen/carbon dioxide coal combustion, *Proceedings of the Combustion Institute*, 31 (2) (2007) 1

1912.

- Article
- Google Scholar

12. [12]

J. Riaza, M. V. Gil, L. Álvarez, C. Pevida, J. J. Pis and F. Rubiera, Oxy-fuel combustion of coal and biomass blends, *Energy*, 41 (1) (2012) 429–435.

- Article
- Google Scholar

13. [13]

L. Álvarez, C. Yin, J. Riaza, C. Pevida, J. J. Pis and F. Rubiera, Biomass co-firing under oxy-fuel conditions: A computational fluid dynamics modelling study and experimental validation, *Fuel Processing Technology*, 120 (2014) 22–33.

- Article
- Google Scholar

14. [14]

Q. Wang, G. Legros, J. Bonnety and C. Morin, Experimental characterization of the different nitrogen dilution effects on soot formation in ethylene diffusion flames, *Proceedings of the Combustion Institute*, 36 (2) (2017) 3227–3235.

- Article
- Google Scholar

15. [15]

D. X. Du, R. L. Axelbaum and C. K. Law, The influence of carbon dioxide and oxygen as additives on soot formation in diffusion flames, *Symposium (International) on Combustion/The Combustion Institute*, 23 (1) (1990) 1501–1507.

- Article
- Google Scholar

16. [16]

K. Al-Qurashi, A. D. Lueking and A. L. Boehman, The deconvolution of the thermal, dilution, and chemical effects of exhaust gas recirculation (EGR) on the reactivity of engine and flame soot, *Combustion and Flame*, 158 (9) (2011) 1696–1704.

- Article
- Google Scholar

17. [17]

Y. Zhou, X. Jin and Q. Jin, Numerical investigation on separate physicochemical effects of carbon dioxide on coal char combustion in O_2/CO_2 environments, *Combustion and Flame*, 167 (2016) 52–59.

- Article
- Google Scholar

18. [18]

F. Shan, Q. Lin, K. Zhou, Y. Wu, W. Fu, P. Zhang, L. Song, C. Shao and B. Yi, An experimental stu[illegible] ignition and combustion of single biomass pellets in air and oxy-fuel, *Fuel*, 188 (2017) 277–284.

- Article
- Google Scholar

19. [19]

J. Riaza, R. Khatami, Y. A. Levendis, L. Álvarez, M. V. Gil, C. Pevida, F. Rubiera and J. J. Pis, Single particle ignition and combustion of anthracite, semi-anthracite and bituminous coals in air and simulated oxy-fuel conditions, *Combustion and Flame*, 161 (4) (2014) 1096–1108.

- Article
- Google Scholar

20. [20]

J. G. Pohlmann, E. Osório, A. C. F. Vilela, M. A. Diez and A. G. Borrego, Pulverized combustion under conventional (O_2/N_2) and oxy-fuel (O_2/CO_2) conditions of biomasses treated at different temperatures, *Fuel Processing Technology*, 155 (2017) 174–182.

- Article
- Google Scholar

21. [21]

M. V. Gil, J. Riaza, L. Álvarez, C. Pevida, J. J. Pis and F. Rubiera, Kinetic models for the oxy-fuel combustion of coal and coal/biomass blend chars obtained in N_2 and CO_2 atmospheres, *Energy*, 48 (1) (2012) 510–518.

- Article
- Google Scholar

22. [22]

J. K. Tanui, P. N. Kioni, T. Mirre and M. Nowitzki, The effect of carbon dioxide on flame propagation speed of wood combustion in a fixed bed under oxy-fuel conditions, *Fuel Processing Technology*, 179 (2018) 285–295.

- Article
- Google Scholar

23. [23]

R. M. Park, R. M. Carroll, P. Bliss, G. W. Burns, R. R. Desmaris, F. B. Hall, M. B. Herzkovitz, D. MacKenzie, E. F. McGuire, R. P. Reed, L. L. Sparks and T. P. Wang (eds.), *ASTM MNL12 — Manual on the Use of Thermocouples in Temperature Measurement,* Fourth Ed., Sponsored by ASTM Committee E20 on Temperature Measurement, West Conshohocken, USA (1993).

- Google Scholar

24. [24]

CD-Adapco, *STAR CCM+ Version 11.04*, www.cd-adapco.com (2017).

- Google Scholar

25. [25]

T. F. Smith, Z. F. Shen and J. N. Friedman, Evaluation of coefficients for the weighted sum of gray gases model, *J. Heat Transf.*, 104 (4) (1982) 602–608.

- Article
- Google Scholar

26. [26]

R. Mehrabian, A. Shiehnejadhesar, R. Scharler and I. Obernberger, Multi-physics modelling of packed bed biomass combustion, *Fuel*, 122 (2014) 164–178.

- Article
- Google Scholar

27. [27]

R. Johansson, H. Thunman and B. Leckner, Influence of intraparticle gradients in modeling of fixed bed combustion, *Combustion and Flame*, 149 (2007) 49–62.

- Article
- Google Scholar

28. [28]

M. Gómez, J. Porteiro, D. de la Cuesta, D. Patiño and J. Míguez, Numerical simulation of the combustion process of a pellet-drop-feed boiler, *Fuel*, 184 (2016) 987–999.

- Article
- Google Scholar

29. [29]

A. H. Mahmoudi, M. Markovic, B. Peters and G. Brem, An experimental and numerical study of wood combustion in a fixed bed using Euler-Lagrange approach (XDEM), *Fuel*, 150 (2015) 573–582.

- Article
- Google Scholar

30. [30]

A. H. Mahmoudi, F. Hoffmann, M. Markovic, B. Peters and G. Brem, Numerical modeling of self-heating and self-ignition in a packed-bed of biomass using XDEM, *Combustion and Flame*, 163 (2016) 358–369.

- Article
- Google Scholar

31. [31]

G. P. Smith, D. M. Golden, M. Frenklach, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C. T. Bowman, R. K. Hanson, S. Song, W. C. Gardiner Jr., V. V. Lissianski and Z. Qin, *GRI-MECH 3.0*, http://www.me.berkeley.edu/gri_mech/ (1999).

- Google Scholar

32. [32]

C. K. Westbrook and F. L. Dryer, Chemical kinetic modeling of hydrocarbon combustion, *Prog. Energy Combust. Sci.*, 10 (1) (1984) 1–57.

- Article
- Google Scholar

33. [33]

D. D. Evans and H. W. Emmons, Combustion of wood charcoal, *Fire Research*, 1 (1977) 57–66.

- Google Scholar

34. [34]

T. Suda, K. Masuko, J. Sato, A. Yamamoto and K. Okazaki, Effect of carbon dioxide on flame pro n of pulverized coal clouds in CO_2/O_2 combustion, *Fuel*, 86 (2007) 2008–2015.

- Article
- Google Scholar

35. [35]

N. Lallemant, A. Sayre and R. Weber, Evaluation of emissivity correlations for H_2O-CO_2-N_2/air mixtures and coupling with solution methods of the radiative transfer equation, *Prog. Energy Combust. Sci.*, 22 (6) (1996) 543–574.

- Article
- Google Scholar

Download references

Acknowledgments

This work was financially supported by both Dedan Kimathi University of Technology, Kenya and Technische Hochschule Wildau, Germany. The first Author would like to thank German Academic Exchange Service (DAAD) for the financial support for his stay in Technische Hochschule Wildau, Germany.

Author information

Affiliations

1. Department of Mechanical Engineering, Dedan Kimathi University of Technology, P.O. Box 657-10100, Nyeri, Kenya
   - Josephat Kipyegon Tanui
   - & Paul Ndirangu Kioni
2. Fachbereich Ingenieur- und Naturwissenschaften, Technische Hochschule Wildau, Hochschulring 1, 15745, Wildau, Germany
   - Thomas Mirre
   - & Mario Nowitzki

Authors

1. Search for Josephat Kipyegon Tanui in:
   - PubMed •
   - Google Scholar
2. Search for Paul Ndirangu Kioni in:
   - PubMed •
   - Google Scholar
3. Search for Thomas Mirre in:
   - PubMed •
   - Google Scholar
4. Search for Mario Nowitzki in:
   - PubMed •
   - Google Scholar

Corresponding author

Correspondence to Josephat Kipyegon Tanui.

Additional information

Recommended by Associate Editor Jeong Park

J. K. Tanui

received his B.Sc. and M.Sc. in Mechanical Engineering from Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya, in 2009 and 2013, respectively. He is currently doing his Ph.D. at Dedan Kimathi University of Technology (DeKUT) with special arrangements to carry out some research at Technische Hochschule Wildau, Germany. His research interests include combustion and gasification of solid fuels, biofuels combustion and kinetics, emissions and pollutant formation in fuels.

P. N. Kioni

received his B.Sc. in Mechanical Engineering from University of Nairobi, Kenya, in 1988, and Ph.D. from Cambridge University, United Kingdom, in 1994. He is a Professor of Mechanical Engineering at DeKUT. His research interests include studies of reacting flows.

T. Mirre

received his Dipl.-Ing. in power plant technology and transformation of energy, special nuclear technology from Technical University Zittau in 1982. In 1992 he became a Professor in the Faculty of Mechanical Engineering at the University of Applied Science (UAS) Wildau and from 1998 to 2010 he was the Dean of the faculty. His subject area is thermodynamics, flows and turbo-engines.

M. Nowitzki

received his Dipl.-Ing. in Process Engineering from UAS Wildau in 2005. He is currently working at UAS Wildau and doing his Dr.-Ing. at the Brandenburg University of Technology Cottbus-Senftenberg. His research interests include multiphase flow simulation, Tesla microturbines, substance transition in rectification columns and heat transfer.

Rights and permissions

About this article

Cite this article

Tanui, J.K., Kioni, P.N., Mirre, T. *et al.* Chemical, thermal and dilution effects of carbon dioxide in oxy-fuel combustion of wood in a fixed bed. *J Mech Sci Technol* **33,** 6063–6073 (2019) doi:10.1007/s12206-019-1150-z

- Received

  18 February 2019

- Revised

  20 September 2019

- Accepted

  10 October 2019

- Published

  18 December 2019

- Issue Date

  December 2019

- DOI

  https://doi.org/10.1007/s12206-019-1150-z

Share this article

Anyone you share the following link with will be able to read this content:

Get shareable link

Sorry, a shareable link is not currently available for this article.

Copy to clipboard

Provided by the Springer Nature SharedIt content-sharing initiative

Keywords

- Burning rate
- CO_2 effect
- Fixed bed
- Oxy-fuel combustion
- Wood combustion

- Sections
- References

1. International Energy Agency, *World Energy Outlook 2016: Executive Summary*, https://www.iea.org (2016).
   - Google Scholar
2. S. K. Hong, D. S. Noh and J. B. Yang, Experimental study of honeycomb regenerator system for oxy-fuel combustion, *J. of Mechanical Science and Technology*, 27 (4) (2013) 1151–1154.
   - Article
   - Google Scholar
3. S. H. Tak, S. K. Park, T. S. Kim, J. L. Sohn and Y. D. Lee, Performance analyses of oxy-fuel power generation systems including CO_2 capture: Comparison of two cycles using different recirculation fluids, *J. of Mechanical Science and Technology*, 24 (9) (2010) 1947–1954.
   - Article
   - Google Scholar
4. D. Kim and S. Choi, Effect of typical modeling assumptions for pulverized coal char combustion commonly used in commercial CFD codes, *J. of Mechanical Science and Technology*, 29 (11) (2015) 4951–4961.
   - Article
   - Google Scholar
5. R. Ben-Mansour, P. Ahmed, M. A. Habib and A. Jamal, Oxy-combustion of liquid fuel in an ion transport membrane reactor, *International J. of Energy and*

Environmental Engineering, 9 (2018) 21–37.

- Article
- Google Scholar

6. R. Marsh, J. Runyon, A. Giles, S. Morris, D. Pugh, A. Valera-Medina and P. Bowen, Premixed methane oxycombustion in nitrogen and carbon dioxide atmospheres: Measurement of operating limits, flame location and emissions, *Proceedings of the Combustion Institute*, 36 (3) (2017) 3949–3958.

   - Article
   - Google Scholar

7. G. Scheffknecht, L. Al-Makhadmeh, U. Schnell and J. Maier, Oxy-fuel coal combustion — A review of the current state-of-the-art, *International J. of Greenhouse Gas Control*, 5 (2011) 16–35.

   - Article
   - Google Scholar

8. J. Ahn, H. J. Kim and K. S. Choi, Oxy-fuel combustion boiler for CO_2 capturing: 50 kW-class model test and numerical simulation, *J. of Mechanical Science and Technology*, 24 (10) (2010) 2135–2141.

   - Article
   - Google Scholar

9. S. K. Hong, K. G. Kang, D. S. Noh, E. K. Lee and H. S. Ryou, Development of an oxy-fuel combustor with fuel preheating for regenerator system, *J. of Mechanical Science and Technology*, 29 (10) (2015) 4555–4559.

   - Article
   - Google Scholar

10. S. Park, J. A. Kim, C. Ryu, W. Yang, Y. J. Kim and S. Seo, Effects of gas and particle emissions on wall radiative heat flux in oxy-fuel combustion, *J. of Mechanical Science and Technology*, 26 (5) (2012) 1633–1641.

    - Article
    - Google Scholar

11. A. Molina and C. R. Shaddix, Ignition and devolatilization of pulverized bituminous coal particles during oxygen/carbon dioxide coal combustion, *Proceedings of the Combustion Institute*, 31 (2) (2007) 1905–1912.

    - Article
    - Google Scholar

12. J. Riaza, M. V. Gil, L. Álvarez, C. Pevida, J. J. Pis and F. Rubiera, Oxy-fuel combustion of coal and biomass blends, *Energy*, 41 (1) (2012) 429–435.

    - Article
    - Google Scholar

13. L. Álvarez, C. Yin, J. Riaza, C. Pevida, J. J. Pis and F. Rubiera, Biomass co-firing under oxy-fuel conditions: A computational fluid dynamics modelling study and experimental validation, *Fuel Processing Technology*, 120 (2014) 22–33.

    - Article
    - Google Scholar

14. Q. Wang, G. Legros, J. Bonnety and C. Morin, Experimental characterization of the different nitrogen dilution effects on soot formation in ethylene diffusion flames, *Proceedings of the Combustion Institute*, 36 (2) (2017) 3227–3235.

    - Article
    - Google Scholar

15. D. X. Du, R. L. Axelbaum and C. K. Law, The influence of carbon dioxide and oxygen as additives on soot formation in diffusion flames, *Symposium (International) on Combustion/The Combustion Institute*, 23 (1) (1990) 1501–1507.

    - Article
    - Google Scholar

16. K. Al-Qurashi, A. D. Lueking and A. L. Boehman, The deconvolution of the thermal, dilution, and chemical effects of exhaust gas recirculation (EGR) on the reactivity of engine and flame soot,

Combustion and Flame, 158 (9) (2011) 1696–1704.

- Article
- Google Scholar

17. Y. Zhou, X. Jin and Q. Jin, Numerical investigation on separate physicochemical effects of carbon dioxide on coal char combustion in O_2/CO_2 environments, *Combustion and Flame*, 167 (2016) 52–59.

    - Article
    - Google Scholar

18. F. Shan, Q. Lin, K. Zhou, Y. Wu, W. Fu, P. Zhang, L. Song, C. Shao and B. Yi, An experimental study of ignition and combustion of single biomass pellets in air and oxy-fuel, *Fuel*, 188 (2017) 277–284.

    - Article
    - Google Scholar

19. J. Riaza, R. Khatami, Y. A. Levendis, L. Álvarez, M. V. Gil, C. Pevida, F. Rubiera and J. J. Pis, Single particle ignition and combustion of anthracite, semi-anthracite and bituminous coals in air and simulated oxy-fuel conditions, *Combustion and Flame*, 161 (4) (2014) 1096–1108.

    - Article
    - Google Scholar

20. J. G. Pohlmann, E. Osório, A. C. F. Vilela, M. A. Diez and A. G. Borrego, Pulverized combustion under conventional (O_2/N_2) and oxy-fuel (O_2/CO_2) conditions of biomasses treated at different temperatures, *Fuel Processing Technology*, 155 (2017) 174–182.

    - Article
    - Google Scholar

21. M. V. Gil, J. Riaza, L. Álvarez, C. Pevida, J. J. Pis and F. Rubiera, Kinetic models for the oxy-fuel combustion of coal and coal/biomass blend chars obtained in N_2 and CO_2 atmospheres, *Energy*, 48 (1) (2012) 510–518.

    - Article

- Google Scholar

22. J. K. Tanui, P. N. Kioni, T. Mirre and M. Nowitzki, The effect of carbon dioxide on flame propagation speed of wood combustion in a fixed bed under oxy-fuel conditions, *Fuel Processing Technology*, 179 (2018) 285–295.

    - Article
    - Google Scholar

23. R. M. Park, R. M. Carroll, P. Bliss, G. W. Burns, R. R. Desmaris, F. B. Hall, M. B. Herzkovitz, D. MacKenzie, E. F. McGuire, R. P. Reed, L. L. Sparks and T. P. Wang (eds.), *ASTM MNL12 — Manual on the Use of Thermocouples in Temperature Measurement,* Fourth Ed., Sponsored by ASTM Committee E20 on Temperature Measurement, West Conshohocken, USA (1993).

    - Google Scholar

24. CD-Adapco, *STAR CCM+ Version 11.04*, www.cd-adapco.com (2017).

    - Google Scholar

25. T. F. Smith, Z. F. Shen and J. N. Friedman, Evaluation of coefficients for the weighted sum of gray gases model, *J. Heat Transf.*, 104 (4) (1982) 602–608.

    - Article
    - Google Scholar

26. R. Mehrabian, A. Shiehnejadhesar, R. Scharler and I. Obernberger, Multi-physics modelling of packed bed biomass combustion, *Fuel*, 122 (2014) 164–178.

    - Article
    - Google Scholar

27. R. Johansson, H. Thunman and B. Leckner, Influence of intraparticle gradients in modeling of fixed bed combustion, *Combustion and Flame*, 149 (2007) 49–62.

    - Article
    - Google Scholar

28. M. Gómez, J. Porteiro, D. de la Cuesta, D. Patiño and J. Míguez, Numerical simulation of the combustion process of a pellet-drop-feed boiler, *Fuel*, 184 (2016) 987–999.

- Article
- Google Scholar

29. A. H. Mahmoudi, M. Markovic, B. Peters and G. Brem, An experimental and numerical study of wood combustion in a fixed bed using Euler-Lagrange approach (XDEM), *Fuel*, 150 (2015) 573–582.

- Article
- Google Scholar

30. A. H. Mahmoudi, F. Hoffmann, M. Markovic, B. Peters and G. Brem, Numerical modeling of self-heating and self-ignition in a packed-bed of biomass using XDEM, *Combustion and Flame*, 163 (2016) 358–369.

- Article
- Google Scholar

31. G. P. Smith, D. M. Golden, M. Frenklach, N. W. Moriarty, B. Eiteneer, M. Goldenberg, C. T. Bowman, R. K. Hanson, S. Song, W. C. Gardiner Jr., V. V. Lissianski and Z. Qin, *GRI-MECH 3.0*, http://www.me.berkeley.edu/gri_mech/ (1999).

- Google Scholar

32. C. K. Westbrook and F. L. Dryer, Chemical kinetic modeling of hydrocarbon combustion, *Prog. Energy Combust. Sci.*, 10 (1) (1984) 1–57.

- Article
- Google Scholar

33. D. D. Evans and H. W. Emmons, Combustion of wood charcoal, *Fire Research*, 1 (1977) 57–66.

- Google Scholar

34. T. Suda, K. Masuko, J. Sato, A. Yamamoto and K. Okazaki, Effect of carbon dioxide on flame propagation of pulverized coal

clouds in CO_2/O_2 combustion, *Fuel*, 86 (2007) 2008–2015.

- Article
- Google Scholar

35. N. Lallemant, A. Sayre and R. Weber, Evaluation of emissivity correlations for H_2O-CO_2-N_2/air mixtures and coupling with solution methods of the radiative transfer equation, *Prog. Energy Combust. Sci.*, 22 (6) (1996) 543–574.

    - Article
    - Google Scholar