

DECLARATION OF JUNE ANN MUNFORD

1. My name is June Ann Munford. I am over the age of 18, have personal knowledge of the facts set forth herein, and am competent to testify to the same.
2. I have been retained on behalf of the Petitioner to provide assistance in the above-illustrated matter in establishing the authenticity and public availability of the documents discussed in this declaration. I am being compensated for my services in this matter at the rate of \$200.00 per hour plus reasonable expenses. My statements are objective, and my compensation does not depend on the outcome of this matter.
3. I declare under penalty of perjury that the foregoing is true and correct. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.
4. I earned a Master of Library and Information Science (MLIS) from the University of Wisconsin-Milwaukee in 2009. I have over ten years of

experience in the library/information science field. Beginning in 2004, I have served in various positions in the public library sector including Assistant Librarian, Youth Services Librarian and Library Director. I have attached my Curriculum Vitae as Appendix CV.

5. During my career in the library profession, I have been responsible for materials acquisition for multiple libraries. In that position, I have cataloged, purchased and processed incoming library works. That includes purchasing materials directly from vendors, recording publishing data from the material in question, creating detailed material records for library catalogs and physically preparing that material for circulation. In addition to my experience in acquisitions, I was also responsible for analyzing large collections of library materials, tailoring library records for optimal catalog search performance and creating lending agreements between libraries during my time as a Library Director.
6. I have reviewed Exhibit 1006, a paper entitled "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al as presented at the 14th Greenhouse Gas Control Technologies Conference. According to Exhibit 1006, this conference was held from October 21st – 25th, 2018.

7. Attached hereto as Appendix MARTIN01 is a screen capture of a webpage entitled "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" as hosted on the Social Science Research Network website. I secured these screen captures myself from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3366370.
8. It is my understanding and experience that the Social Science Research Network (hereto referred to as SSRN) and its parent company Elsevier host an online database including academic research papers. In my experience, the metadata supplied by SSRN regarding the items in its database, including date of posting, is known to be reliable. Appendix MARTIN01 is a web page from SSRN describing "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al. According to this page, "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" was first posted to the SSRN website as of April 11, 2019. Appendix MARTIN01 also indicates that this paper has been downloaded 556 times since being posted as of April 11, 2019. Page 1 of Appendix MARTIN01 contains a link entitled 'Download This Paper' which offers a download of a PDF copy of "Progress Update on the Allam Cycle:

Commercialization of NET Power and the NET Power Demonstration Facility".

9. Attached hereto as Appendix MARTIN02 is a PDF copy of "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" obtained by following the link entitled 'Download This Paper' on the SSRN website described as Appendix MARTIN01. I secured this file myself from https://papers.ssrn.com/sol3/Delivery.cfm/Martin_S_Session_1G_-Oxycombustion_ACUpdate_F.pdf?abstractid=3366370&mirid=1.

10. In comparing Exhibit 1006 to Appendix MARTIN02, it is my determination that Exhibit 1006 is a true and correct copy of "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al. Exhibit 1006 and Appendix MARTIN02 are identical in title, author, text and page length. Both documents can be accurately described by the web page captured in Appendix MARTIN01, a page containing bibliographic information describing "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" as provided by the paper's publisher, SSRN.

11. Attached hereto as Appendix MARTIN03 is a screen capture of a webpage entitled "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" as hosted on the OCLC Worldcat website. I secured these screen captures myself from <https://search.worldcat.org/title/8686834534>.

12. OCLC Worldcat is a web service maintained by OCLC Inc. that serves as an aggregator for library catalog records. Worldcat users can use OCLC's search platform to search thousands of library catalogs with a single query. Worldcat's search platform also offers features such as multi-input search queries and detailed filter options for advanced users to navigate the platform's exhaustive search results. Appendix MARTIN03 is the Worldcat record for "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al as presented at the 14th Greenhouse Gas Control Technologies Conference. This record indicates the Martin paper is available in 98 libraries within the OCLC network. From this Worldcat page, users are able to make interlibrary loan requests from any of these individuals 98 libraries, indicating "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" has been made available to the public in

various regions of North America, the United Kingdom, the Netherlands and Germany.

13. Attached hereto as Appendix MARTIN04 is a screen capture of a webpage entitled "Supercritical CO₂ Demonstration Power Plant on Allam Cycle" as hosted on the ResearchGate website. I secured these screen captures myself from https://www.researchgate.net/publication/338431114_Supercritical_CO2_Demonstration_Power_Plant_on_Allam_Cycle.

14. Appendix MARTIN04 is a page describing a paper entitled "Supercritical CO₂ Demonstration Power Plant on Allam Cycle" by Parikshit Jain as presented at the 2019 International Gas Turbine Congress. This page offers a PDF copy for download of the Jain paper, contained in Appendix MARTIN04 as pages 8-12. Page 1 lists a November 2019 publication date for this paper and page 8 indicates this paper was presented sometime between November 17-22, 2019. Page 12 of Appendix MARTIN04 contains a citation to "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al as presented at the 14th Greenhouse Gas Control Technologies Conference. The existence of this citation indicates the Martin paper was

available to the author of the Jain paper at a date prior to November 17, 2019.

15. Attached hereto as Appendix MARTIN05 is a screen capture of a webpage entitled "Natural Gas-Oxygen Combustion in a Super-Critical Carbon Dioxide Gas Turbine Combustor" as hosted on the EDP Sciences website. I secured these screen captures myself from https://www.e3s-conferences.org/articles/e3sconf/abs/2020/38/e3sconf_hsted2020_01027/e3sconf_hsted2020_01027.html.

16. Appendix MARTIN05 is a page describing a paper entitled "Natural Gas-Oxygen Combustion in a Super-Critical Carbon Dioxide Gas Turbine Combustor" by Ivan Komarov, et al as presented at the 2020 High Speed Turbomachines and Electrical Drives Conference. This page offers a PDF copy for download of the Komarov paper, contained in Appendix MARTIN05 as pages 3-9. Page 1 lists a July 9, 2020 publication date for this paper. Page 8 of Appendix MARTIN04 contains a citation to "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al as presented at the 14th Greenhouse Gas Control Technologies Conference. The existence of this

citation indicates the Martin paper was available to the authors of the Komarov paper at a date prior to July 9, 2020.

17. Appendix MARTIN01 indicates "Progress Update on the Allam Cycle:

Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al was first published on the SSRN's website as of April 11, 2019 and has been downloaded from this site 556 times.

Appendix MARTIN04 indicates the Martin paper was accessible to the author of the Jain paper before November 17, 2019. Appendix MARTIN05 indicates the Martin paper was accessible to the author of the Komarov paper before July 9, 2020. When considering the range of dates represented in Exhibit 1006 and Appendices MARTIN01-05, it is my determination that "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility" by Scott Martin, et al was made available to the public on or around April 11, 2019.

Dated: 12/1/2024



June Ann Munford

APPENDIX CV

To Declaration of June Ann Munford

June A. Munford
Curriculum Vitae

Education

University of Wisconsin-Milwaukee - MS, Library & Information Science, 2009
Milwaukee, WI

- Coursework included cataloging, metadata, data analysis, library systems, management strategies and collection development.
- Specialized in library advocacy, cataloging and public administration.

Grand Valley State University - BA, English Language & Literature, 2008
Allendale, MI

- Coursework included linguistics, documentation and literary analysis.
- Minor in political science with a focus in local-level economics and government.

Professional Experience

Researcher / Expert Witness, October 2017 – present
Freelance ● Pittsburgh, Pennsylvania & Grand Rapids, Michigan

- Material authentication and public accessibility determination. Declarations of authenticity and/or public accessibility provided upon research completion. Experienced with appeals and deposition process.
- Research provided on topics of public library operations, material publication history, digital database services and legacy web resources.
- Past clients include Alston & Bird, Arnold & Porter, Baker Botts, Fish & Richardson, Erise IP, Irell & Manella, O'Melveny & Myers, Perkins-Coie, Pillsbury Winthrop Shaw Pittman and Slayden Grubert Beard.

Library Director, February 2013 - March 2015
Dowagiac District Library ● Dowagiac, Michigan

- Executive administrator of the Dowagiac District Library. Located in

Southwest Michigan, this library has a service area of 13,000, an annual operating budget of over \$400,000 and total assets of approximately \$1,300,000.

- Developed careful budgeting guidelines to produce a 15% surplus during the 2013-2014 & 2014-2015 fiscal years while being audited.
- Using this budget surplus, oversaw significant library investments including the purchase of property for a future building site, demolition of existing buildings and building renovation projects on the current facility.
- Led the organization and digitization of the library's archival records.
- Served as the public representative for the library, developing business relationships with local school, museum and tribal government entities.
- Developed an objective-based analysis system for measuring library services - including a full collection analysis of the library's 50,000+ circulating items and their records.

November 2010 - January 2013

Librarian & Branch Manager, Anchorage Public Library • Anchorage, Alaska

- Headed the 2013 Anchorage Reads community reading campaign including event planning, staging public performances and creating marketing materials for mass distribution.
- Co-led the social media department of the library's marketing team, drafting social media guidelines, creating original content and instituting long-term planning via content calendars.
- Developed business relationships with The Boys & Girls Club, Anchorage School District and the US Army to establish summer reading programs for children.

June 2004 - September 2005, September 2006 - October 2013

Library Assistant, Hart Area Public Library

Hart, MI

- Responsible for verifying imported MARC records and original MARC

cataloging for the local-level collection as well as the Michigan Electronic Library.

- Handled OCLC Worldcat interlibrary loan requests & fulfillment via ongoing communication with lending libraries.

Professional Involvement

Alaska Library Association - Anchorage Chapter

- Treasurer, 2012

Library Of Michigan

- Level VII Certification, 2008
- Level II Certification, 2013

Michigan Library Association Annual Conference 2014

- New Directors Conference Panel Member

Southwest Michigan Library Cooperative

- Represented the Dowagiac District Library, 2013-2015

Professional Development

Library Of Michigan Beginning Workshop, May 2008

Petoskey, MI

- Received training in cataloging, local history, collection management, children's literacy and reference service.

Public Library Association Intensive Library Management Training, October 2011

Nashville, TN

- Attended a five-day workshop focused on strategic planning, staff management, statistical analysis, collections and cataloging theory.

Alaska Library Association Annual Conference 2012 - Fairbanks, February 2012

Fairbanks, AK

- Attended seminars on EBSCO advanced search methods, budgeting, cataloging, database usage and marketing.

Depositions

2019 • Fish & Richardson

Apple v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282 and 39521-00421IP2)

2019 • Erise IP

Implicit, LLC v. Netscout Systems, Inc (Civil Action No. 2:18-cv-53-JRG)

2019 • Perkins-Coie

Adobe Inc. v. RAH Color Technologies LLC (Cases IPR2019-00627, IPR2019-00628, IPR2019-00629 and IPR2019-00646)

2020 • O'Melveny & Myers

Maxell, Ltd. v. Apple Inc. (Case No. 5:19-cv-00036-RWS)

2021 • Pillsbury Winthrop Shaw Pittman LLP

Intel v. SRC (IPR2020-1449)

2022 • Perkins-Coie

Realtek v. Future Link (IPR2021-01182)

2023 • Fish & Richardson

Neuroderm Ltd. v. Abbvie, Inc (Case No. PGR2022-00040)

2023 • Fish & Richardson

Nearmap US Inc. v. Pictometry International Corp. (IPR2022-00735)

2023 • Fish & Richardson

Samsung Electronics v. MemoryWeb LLC (Case No. 39843-0136PS1)

2023 ● Pillsbury Winthrop Shaw Whitman LLP

Gravel Rating Systems v. Costco Wholesale Corp. (Civil Action No. 4:21-cv-149-ALM)

2024 ● Willkie-Farr

Netflix, Inc. v. VideoLabs. Inc. (IPR2023-00628)

Limited Case and Clientele History

Alston & Bird

- Ericsson

v. Collision Communications (IPR2022-01233)

- Nokia

v. Neptune Subsea, Xtera (Case No. 1:17-cv-01876)

- Universal Electronics Inc

v. Roku Inc (IPR2022-00818)

Arnold & Porter

- Ivantis

v. Glaukos (Case No. 8:18-cv-00620)

- Samsung

v. Jawbone (Case No. 2:21-cv-00186)

Benesch Friedlander Coplan & Aronoff

- Voyis
 - v. Cathx (Case No. 5:21-cv-00077-RWS)

Deschert LLP

- Smaxtec Animal Care
 - v. ST Reproductive Technologies, LLC (IPR2024-00885)

Erise I.P.

- Apple
 - v. Ericsson Inc. (IPR2022-00715)
 - v. Future Link Systems (IPRs 6317804, 6622108, 6807505, and 7917680)
 - v. INVT (Case No. 20-1881)
 - v. Navblazer LLC (IPR2020-01253)
 - v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)
 - v. Quest Nettech Corp (Case No. 2:19-cv-00118-JRG)
 - v. Telefonaktiebolaget LM Ericsson (IPR2022-00275)
 - v. Theta IP, LLC (IPR2024-00818)
- Fanduel
 - v. CGT (Case No. 19-1393)
- Garmin
 - v. Phillips North America LLC (Case No. 2:19-cv-6301-AB-KS)

- Netscout
 - v. Longhorn HD LLC (Case No. 2:20-cv-00349)
 - v. Implicit, LLC (Civil Action No. 2:18-cv-53-JRG)
- Sony Interactive Entertainment LLC
 - v. Bot M8 LLC (IPR2020-01288)
 - v. Infernal Technology LLC (Case No. 2:19-CV-00248-JRG)
- Unified Patents
 - v. GE Video Compression (Civil Action No. 2:19-cv-248)

Fish & Richardson

- Apple
 - v. AliveCor (3:21-cv-03958)
 - v. LBS Innovations (Case No. 2:19-cv-00119-JRG-RSP)
 - v. Koss Corporation (IPR2021-00305)
 - v. Masimo (IPR 50095-0012IP1, 50095-0012IP2, 50095-0013IP1, 50095-0013IP2, 50095-0006IP1, 50095-0135IP1)
 - v. Neonode (Case No. 21-cv-08872-EMC)
 - v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)
- Dell
 - v. Neo Wireless (IPR2022-00616)
- Dish Network
 - v. Entropic Communications, LLC (Case No. 2:2023-CV-01043)

- v. Realtime Adaptive Streaming (Case No. 1:17-CV-02097-RBJ)
 - v. TQ Delta LLC (Case No. 18-1798)
- Evapco Dry Cooling
 - v. SPG Dry Cooling (IPR2021-00688)
- Genetec
 - v. Sensormatic Electronics (Case No. 1:20-CV-00760)
- Huawei
 - v. Bell Northern Research LLC (IPR2019-01174)
- Kianxis
 - v. Blue Yonder (Case No. 3:20-cv-03636)
- LG Electronics
 - v. Bell Northern Research LLC (Case No. 3:18-cv-2864-CAB-BLM)
- Metaswitch
 - v. Sonus Networks (IPR2018-01719)
- Microsoft
 - v. Throughputer Inc (IPR2022-00757)
- Mom Enterprises
 - v. Ddrops Company (Case No. 1:22-cv-00332)
- MLC Intellectual Property

- v. MicronTech (Case No. 3:14-cv-03657-SI)
- Nearmap Inc
 - v. EagleView Technologies (IPR2022-01009)
- Neuroderm Ltd.
 - v. Abbvie, Inc (Case No. PGR2022-00040)
- Realtek Semiconductor
 - v. Future Link (IPR2021-01182)
- Quectel
 - v. Koninklijke Philips (Case No. 1:20-cv-01710)
- Samsung
 - v. Aire Technology (IPR2022-00877)
 - v. Bell Northern Research (Case No. 2:19-cv-00286-JRG)
 - v. Communication Technologies Inc (IPR2022-01221)
 - v. Jawbone Innovations (IPR2022-00865)
 - v. MemoryWeb LLC (IPR2022-00885)
 - v. Dodots Licensing Solutions (IPR2023-00701)
 - v. Telefonaktiebolaget LM Ericsson (IPR2021-00615)
- Texas Instruments
 - v. Vantage Micro LLC (IPR2020-01261)
- Xilinx
 - v. Sentient Sensors LCC (Case No. 1:22-cv-00173)

Groombridge Wu

- Nearmap

v. Eagle View Technologies Inc. and Pictometry International Corp.
(Case No. 2:21-cv-00283-TS-DAO)

Irell & Manella

- Curium

O'Melveny & Myers

- Apple

v. Maxell (Case No. 5:19-cv-00036-RWS)

- Disney Media & Entertainment Distribution LLC

v. Digital Media Technology Holdings, LLC (Case No. 2:22-cv-01642)

- Micron Technology Inc.

v. Besang Inc (IPR2023-00900)

- Samsung

v. Daedalus Prime LLC (1335 Investigation)

Perkins-Coie

- Amazon

v. Nokia (IPR2024-00847 and IPR2024-00848)

- Heru Industries
 - v. The UAB Research Foundation (IPR2022-01148)
- Intel Corporation
 - v. BeSang Inc. (IPR2023-00991)
 - v. BitMICRO (Case No. 5:23-cv-00625)
 - v. Telefonaktiebolaget L M Ericsson (IPR2024-00610)
- Realtek Semiconductor
 - v. Future Link (IPR2021-01182)
- Twitter Inc
 - v. VOIP-Pal.com (Case No. 3:20-cv-02397-JD)
- TCL Industries
 - v. Koninklijke Philips NV (IPR2021-00495, IPR2021-00496 and IPR2021-00497)

Pillsbury Winthrop Shaw Pittman

- Intel
 - v. FG SRC LLC (Case No. 6:20-cv-00315)
- Gravel Rating Systems
 - v. Costco (Case No. 4:21-cv-149)
 - v. Lowe's Home Centers (Case No. 4:21-cv-150)
 - v. T-Mobile USA (Case No. 4:21-cv-152)
 - v. Kohl's Inc. (Case No. 4:21-cv-258)
 - v. Under Armor (Case No. 4:21-cv-356)

Quinn Emanuel

- ServiceNow, Inc.
v. InQusient, Inc. (Case No. 22-900-CJB)
- Wolfsped
v. The Trustees of Purdue University (Case No. 1:2021-cv-00840)

Sheppard, Mullin, Richter & Hampton LLP

- Cadence Design Systems Inc.
v. Semiconductor Design Technologies (Case No. 3:23-cv-01001)

Stern, Kessler, Goldstein & Fox

- Preliminary Research

Willkie, Farr & Gallagher LLP

- Neurent
v. The Foundry, LLC (IPR2024-00669)
- Netflix, Inc.
v. VideoLabs, Inc. (IPR2023-00628)

EXHIBIT MARTIN01

To Declaration of June Ann Munford

[Product & Services](#)[Subscribe](#)[Submit a paper](#)[Browse](#)[Rankings](#)[Blog ↗](#)[Contact](#)[Create account](#)[Sign in](#)[Download This Paper](#)[Open PDF in Browser](#)[Add Paper to My Library](#)Share: [f](#) [t](#) [e](#) [o](#)

Progress Update on the Allam Cycle: Commercialization of Net Power and the Net Power Demonstration Facility

14th Greenhouse Gas Control Technologies Conference Melbourne 21-26 October 2018 (GHGT-14)

14 Pages • Posted: 11 Apr 2019

Scott Martin

8 Rivers Capital, LLC

Brock Forrest

8 Rivers Capital, LLC

Navid Rafati

8 Rivers Capital, LLC

Xijia Lu

8 Rivers Capital, LLC

Jeremy Fetvedt

8 Rivers Capital, LLC

Mike McGroddy

8 Rivers Capital, LLC

Bill Brown

8 Rivers Capital, LLC

Rodney Allam

8 Rivers Capital, LLC

Damian Beauchamp

8 Rivers Capital, LLC

David Freed

8 Rivers Capital, LLC

Abstract

Abstract not provided to SSRN.

Keywords: Capture only CCS projects, GHGT-14**Suggested Citation:**

Martin, Scott and Forrest, Brock and Rafati, Navid and Lu, Xijia and Fetvedt, Jeremy and McGroddy, Mike and Brown, Bill and Allam, Rodney and Beauchamp, Damian and Freed, David, Progress Update on the Allam Cycle: Commercialization of Net Power and the Net Power Demonstration Facility. 14th Greenhouse Gas Control Technologies Conference Melbourne 21-26 October 2018 (GHGT-14), Available at SSRN: <https://ssrn.com/abstract=3366370> or <http://dx.doi.org/10.2139/ssrn.3366370>

[Show Contact Information](#) >

Do you have a job opening that you would like to promote on SSRN?

[Place Job Opening](#)

Paper statistics

DOWNLOADS	ABSTRACT VIEWS	RANK
556	1,533	99,519

1 Citations

13 References

PlumX Metrics



Related ejournals

Sustainability & Economics ejournal

[Follow](#)

Politics & Energy ejournal

[Follow](#)[View more >](#)[Download This Paper](#)[Open PDF in Browser](#)

13 References

1. R J Allam , M R Palmer , G W Brown , J Fetvedt , D Freed , H Nomoto , M Itoh , N Okita , C Jones
High Efficiency and Low Cost of Electricity Generation from Fossil Fuels While Eliminating
Atmospheric Emissions, Including Carbon Dioxide
Energy Procedia , volume 37 , p. 1135 - 1149 Posted: 2013

[Crossref](#) ↗

2. R Allam , S Martin , B Forrest , J Fetvedt , X Lu , D Freed , G W Brown , T Sasaki , M Itoh , J Manning
Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency
Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture
Energy Procedia , volume 114 , p. 5948 - 5966 Posted: 2017
[Crossref](#) ↗
3. X Lu , B Forrest , S Martin , J Fetvedt , M McGroddy , D Freed
Integration and Optimization of Coal Gasification Systems with a Near-Zero Emissions Supercritical Carbon Dioxide Power Cycle
Posted: 2016
[Crossref](#) ↗
4. T Sasaki , M Itoh , H Maeda , J Tominaga , D Saito , Y Niizeki
Development of Turbine and Combustor for a Semi-Closed Recuperated Brayton Cycle of Supercritical Carbon Dioxide Posted:
2017
[Crossref](#) ↗
5. C S
Initiative and C. The Global, Global Roadmap for Implementing CO2 Utilization Posted: 2016
6. Natural Gas Resources and Production Prospects Posted: 2008
7. W F J Burgers , P S Northrop , H S Kheshgi , J A Valencia
Worldwide development potential for sour gas
Energy Procedia , volume 4 , p. 2178 - 2184 Posted: 2011
[Crossref](#) ↗
8. J D Laumb , M J Holmes , J J Stanislawski , X Lu , B Forrest , M McGroddy
Supercritical CO2 Cycles for Power Production
Energy Procedia , volume 114 , p. 573 - 580 Posted: 2017
[Crossref](#) ↗
9. J Fetvedt
Coal Syngas Combustor Development for High-Pressure
Oxy-Fuel SCO2 Cycle Applications Posted: 2014
10. H Abdul-Sater , J Lenertz , C Bonilha , X Lu , J Fetvedt
A CFD Simulation of Coal Syngas OxyCombustion In a High-Pressure Supercritical CO2 Environment Posted: 2017
[Crossref](#) ↗
11. X Lu , S Martin , M McGroddy , M Swanson , J Stanislawski , J Laumb
Testing of a Novel Post Combustion Acid Removal Process for the Direct-Fired, Oxy-Combustion
Allam Cycle Power Generation System
Journal of Engineering for Gas Turbines and Power Posted: 2017
[Crossref](#) ↗
12. M P B F M M Lu
A Novel Power Generation System Utilizing Un-treated Sour Gas Fuel
SPE-192823-MS, ABU DHABI INTERNATIONAL PETROLEUM EXHIBITION & CONFERENCE 12-15 NOVEMBER Posted: 2018
13. G Collodi , G Azzaro , N Ferrari , S Santos
Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as
Feedstock and Fuel
Energy Procedia , volume 114 , p. 2690 - 2712 Posted: 2017
[Crossref](#) ↗

1 Citations

1. Ivan Komarov , Daria Kharlamova , Bulat Makhmutov , Sofia Shabalova , Ilya Kaplanovich , A. Drozdov
Natural Gas-Oxygen Combustion in a Super-Critical Carbon Dioxide Gas Turbine Combustor
E3S Web of Conferences , volume 178 , p. 01027 Posted: 2020
[Crossref](#) ↗

ELSEVIER

[Copyright](#) [Terms and Conditions](#) [Privacy Policy](#)

All content on this site: Copyright © 2024 Elsevier Inc., its licensors, and contributors. All rights are reserved, including those for text and data mining, AI training, and similar technologies. For all open access content, the Creative Commons licensing terms apply.

We use cookies to help provide and enhance our service and tailor content.

To learn more, visit [Cookie settings](#) | [Your Privacy Choices](#). ↗



EXHIBIT MARTIN02

To Declaration of June Ann Munford



14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility

Scott Martin*, Brock Forrest, Navid Rafati, Xijia Lu, Jeremy Fetvedt, Mike McGroddy, Bill Brown, Rodney Allam, Damian Beauchamp, David Freed[◇]

8 Rivers, 406 Blackwell Street, Crowe Building 4th Floor, Durham NC 27701 USA

Abstract

The Allam Cycle is a highly-recuperated, oxy-fuel, semi-closed supercritical CO₂ Brayton cycle that offers significant advantages over traditional power cycles, including high efficiencies, low capital costs, low or no water consumption, and elimination of all air emissions, including CO₂. The natural gas cycle, under commercialization by NET Power, was first presented at GHGT-11 as a novel cycle under development. Progress on the overall cycle design and on the design and construction of a 50 MWth demonstration plant was presented and published at GHGT-13. This paper will present the final constructed design of the demonstration plant, as well as an update on the commissioning, start-up and operation of the facility, underway as of January 2018. It will provide further updates on the commercial design of a NET Power facility. Tangentially, 8 Rivers has pursued work inspired by the aspirations of the Allam Cycle – creating new cycle designs, new CO₂ uses, concepts in clean sour gas combustion, and the clean production of chemical and industrial commodities such as hydrogen and urea.

Keywords: Supercritical, carbon, CCS, Carbon dioxide, demonstration, natural gas, coal, fuel, clean, capture, sequestration, supercritical, CO₂, Power, Energy, hydrogen, NET Power, McDermott, Exelon, 8 Rivers, Toshiba

1. Introduction

In 2008, inspired by the opportunities pouring forth from the American Recovery and Reinvestment Act in the United States, a team at 8 Rivers set out to develop an idea for a new type of clean coal project, setting aspirational goals for a cycle that could create cheap and clean carbon-based energy for the world. The team was discouraged by existing concepts for emissions capture, which largely focused on correcting known processes through technologies such as post combustion carbon capture – processes that both significantly downgraded performance and increased capital cost. While this was and remains today the typical approach to emissions capture, ballooning costs create more and more difficult returns on investment. In most cases, these modified plants are infeasible without heavy subsidization or a cost of CO₂ well above the current market price. The team wanted to find a solution that could stand up on its own.

* Corresponding author. Tel.: +1-919-667-1800

E-mail address: scott.martin@8rivers.com

[◇] Independent

While the team believed they could capture emissions for no extra cost, doing so required pursuing a completely new design paradigm. The cycle that evolved was the Allam Cycle, named after its lead inventor, Rodney Allam. While the original design proposed using gasified coal syngas as the principal fuel source, it was determined that a concept for natural gas would provide a more feasible short term path to commercialization, and natural gas was emerging as the dominant fuel on the global power generation scene. NET Power was stood up as the commercial entity that would bring the natural gas Allam Cycle technology to market. Commercial interest followed suit. In 2011, Toshiba joined as technology partner to design and build the first-of-a-kind supercritical CO₂ turbine specific to the cycle. In 2012, NET Power saw its first major investment of \$50 million from McDermott International (formerly CB&I; formerly The Shaw Group). The investment provided the funding necessary to begin developing a demonstration NET Power facility. Then, in 2014, Exelon Corporation joined the company, providing a \$90 million investment and further in-kind support to ensure the technology could be brought through demonstration scale. Now, four years later, the demonstration plant has completed its first operational phase to prove out the new Toshiba combustor and integrated operation and controllability of the cycle. The next stage of testing, set to begin in Q4 of 2018, will test the cycle in its entirety.

The Allam Cycle was developed with the aim of producing power at a cost competitive with existing best-in-class, non-carbon capture power generation technologies while inherently capturing all carbon and non-carbon emissions for no additional cost. Based on the advancement of NET Power and the Allam Cycle to date, 8 Rivers has applied the same innovation approach to adjacent and related markets, generating several new innovative clean energy processes. Work on novel CO₂ uses, fuel clean-up, combustion, and hydrogen production technologies has taken place, with an overview of that work provided in this paper.

2. Overview of the Allam Cycle

The Allam Cycle is a highly-recuperated, oxy-fuel, semi-closed supercritical CO₂ Brayton cycle that offers significant advantages over traditional power cycles, including high efficiencies, low capital costs, low or no water consumption, and the near elimination of all air emissions while capturing near all generated CO₂. The natural gas cycle, under commercialization by NET Power, was first presented at GHGT-11 as a novel cycle under development [1]. Progress on the overall cycle design and the design and construction of a 50 MWth demonstration plant was presented and published at GHGT-13 [2]. This paper will present the final construction of the demonstration plant, as well as an update on the commissioning, start-up and operation of the facility that is underway as of January 2018.

Traditional power cycles, such as natural gas combined cycle, supercritical coal cycle, and integrated gasification combined cycle, require the addition of expensive, efficiency-reducing equipment in order to decrease and capture emissions of carbon dioxide and other pollutants. The Allam Cycle takes a novel approach to reducing emissions from fossil fuel power generation through the use of an oxy-combustion cycle that employs high-pressure supercritical CO₂ as a working fluid in a highly recuperated manner. In this configuration, the cycle is able to reach high performance efficiencies—currently 58.9% net LHV efficiency for natural gas—and the only by-products are liquid water and a stream of nominally pure CO₂ that is already at pipeline pressure as a result of the operating conditions of the cycle. The inherent operational characteristics of the Allam Cycle allows it to avoid the necessity of additional capture, clean-up, and compression systems for CO₂ carbon capture and storage (CCS) or carbon capture utilization and storage (CCUS). The cycle is able to utilize a variety of hydrocarbon fuels, including natural gas, unprocessed raw and sour gas, and gasified solid fuels such as coal or biomass [3]. The result is a power cycle with major advantages over conventional systems that do not capture CO₂.

The 50 MWth NET Power demonstration facility functions to validate both the cycle as a whole as well as the new supercritical carbon dioxide powered turbine and oxy-fuel combustor designed and manufactured by Toshiba [4]. The first stage of testing at the demonstration facility utilized the overall process in addition to a specially designed combustor test stand to accommodate the testing of a standalone Toshiba oxy-fuel combustor in a recirculating fashion akin to the final design and operation of the overall cycle. The next stage, now in progress, utilizes the full cycle design to accommodate integrated hot operation of both the combustor and turbine for full process demonstration.

In addition to the demonstration plant, NET Power has completed a comprehensive pre-FEED (Front End Engineering Design) of the full commercial design which has provided preliminary information on the expected economics of a commercially deployed full scale 300 MWe NET Power natural gas plant.

3. Progress of the Demonstration Natural-Gas-Based Facility

3.1. Combustor Test Rig (CTR) Operations

The NET Power (NP) Demonstration facility began testing in Q2 of 2018. The focus was to test the novel 50 MWth Toshiba combustor in the NET Power recirculating cycle at steady state and transient conditions while receiving dynamic feedback from the cycle's recuperation. The combustor was tested using a special plant layout known as the Combustor Test Rig (CTR), designed by NET Power, 8 Rivers and WSP, and a special combustor test stand designed by Toshiba.

Activities involved operation of the entire balance of plant (BOP), enabling integrated cycle equipment and control system operability to be validated and tuned. Operators fed fuel, oxidant, and recirculating carbon dioxide to the combustor in the semi-closed process. As a substitute for the hot gas path of the turbine, a pressure and temperature release device was employed. By doing so, the plant mimicked the turbine's pressure and temperature letdown due to expansion work, allowing the cycle and combustor to operate in a semi-closed fashion per the cycle design, while isolating the turbine from the combustor during testing.

In order to drive the Main CO₂ Compressor mechanically coupled to the turbine, a VFD motorized the Toshiba turbine via its generator. Toshiba commissioned and NET Power operated the turbine at fully rated speed with a specialized air coolant supply to counter turbine windage losses during combustor testing. In this way, the hot gas path was isolated from the cycle while process flow was directed through the rest of the plant.

Key Dates:

- May 2018 – First-fire (steady flame) in the Toshiba combustor and subsequent operation of the demonstration plant was achieved May 2018 and announced publicly.
- August 2018 – Combustor testing concluded in early August and it was determined the plant was ready to move on to the next phase of testing.
 - *Note:* the tested combustor is the same as the commercial plant production unit, where 10 – 12 units will operate in parallel.

The operation of the combustor was considered an important risk which was successfully addressed in testing. Furthermore, during test operation the overall plant was controlled continuously through startup, shutdown, and excursions at key operational points, thus serving as further proof of concept. Major equipment underwent 500-900 hours of operation, including 170 hours of runtime with both fuel and oxygen supplied to the cycle. During testing, the maximum coincident pressure and temperature that the main recuperator train experienced was 110 bar (1595 psi) and 538°C (1000°F) respectively.

More importantly, operation of the hot recuperator permitted the demonstration facility to gain critical experience with hot operations. In-situ testing of the working fluid's chemistry was also performed on a multi-second basis monitoring seven key species that can largely impact various turbomachinery performance profiles. While data validation remains ongoing, cycle performance has matched the performance of process simulations predicted by computer modeling, thereby signaling readiness to move on to the next stage of testing.

3.2. Fully Integrated Plant Operations

Since the balance of plant was kept intact for the Combustor Test Rig, major adjustments were only necessary to the area of the plant near the Toshiba combustion turbine. This includes:

- Installation of the high temperature recuperator for operation up to 700°C (1292°F)
- Inspection and refurbishment of the Toshiba combustor and installation at the Toshiba turbine
- High energy piping welds and low energy piping welds for fit-up to turbine and main high temperature recuperator
- I&C changes for high energy piping and turbine (to match the demonstration configuration) as well as software modifications to the plant control systems
- Other plant turnover and refurbishment items and implementation of lessons learned.

Full startup of the plant is expected in Q4 of 2018. Following cold flow, ignition, and low load testing, the plant will be ramped to the synchronization point where energy will be exported to the grid. An overhead view of the demonstration facility is shown in Figure 1.

3.3. Turbine and Plant Performance Run

Following achievement of synchronization, the plant will be loaded to the operational points required for turbine and plant performance testing. This process will entail a semi-continuous run time whereby load following and full load operation will be tested, as the plant will be directly bidding into the local power market. At the conclusion of the turbine and plant performance testing, the plant will be unloaded for planned inspections.

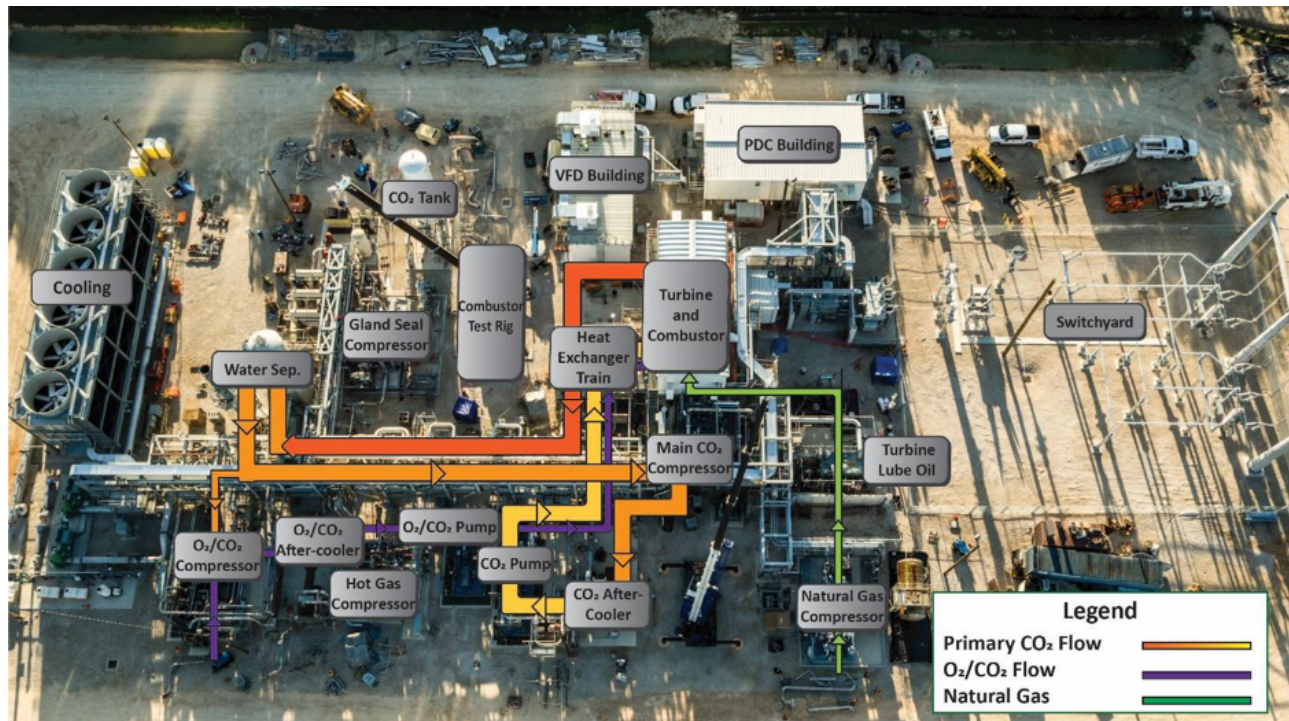


Figure 1: Overhead view of the demonstration facility and key process streams

3.4. Extended Run Operation

Following the performance run, an extended operational period is planned to address the integrity of the plant and its components, as well as early metrics on changes in performance over time and season.

4. Progress of the Commercial Natural-Gas-Based Facility

In 2016, NET Power commissioned CB&I (now McDermott) and partner 8 Rivers to develop a Pre-FEED (Front End Engineering Design) for the first-of-a-kind NET Power Commercial Plant design. The Pre-FEED Phase I was completed in January 2017, culminating in a preliminary design and a design review of in-process work products. Further optimization work was performed in a second iteration of the design (Pre-FEED Phase II) with the main objective of further reducing the capital cost especially for the piping used in high temperature service and its associated labor services. In addition, a design and performance profile specific to a United States customer base was developed and optimized at this stage. The Pre-FEED Phase II scope included the development of early engineering design deliverables such as P&IDs and a plant layout, a Level 2 project schedule, and a Class 4 AACE cost estimate for a nominal 300 MWe NET Power commercial plant. This work was completed in September 2017, and included the detailing of all high energy systems critical to the success of an Allam Cycle-based power plant. Furthermore, it sought to develop a portfolio of operational conditions and characteristics that would entail the co-production of various industrial gases as well as load following profiles for integration with dynamic grids. Ongoing work seeks to address a global customer base with focus points on further compacting the plant footprint, integrating modularization, substituting metallurgy with larger supply chain options, and tailoring plant control to collaborate with renewables powered grid operations.



Figure 2: NET Power nominal 300MWe Commercial Plant Concept

Table 1: First-of-a-kind (FOAK) Commercial Plant Performance

FOAK Commercial Plant Performance	USA* (%)	World (%)
Thermal Heat Input	100%	100%
Turbine Shaft Power	-17.9%	-16.7%
Shaft-mounted CO ₂ compressor and generator	-8%	-7.5%
ASU auxiliary load	-12%	-11.2%
BOP parasitic (pumps, cooling, tower, etc.)	-7%	-6.5%
Net Plant Efficiency (% on LHV)	55.1%	58.9%
Net Plant Heat Rate (LHV)	6,193	5,793

Table 2: Potential Industrial gas cogeneration from a NET Power commercial facility

Industrial Gas Outputs	Approximate Tons/yr
High-pressure, high-purity CO ₂	890,000
High-purity N ₂ , 99.9%	1,500,000
Low-purity N ₂ , 98.6%	2,600,000
High-purity Ar, 99.99%	63,000
High-purity O ₂ , 99.5%	45,000

The Commercial Plant Pre-FEED Phase II was built upon the NET Power natural gas fired supercritical CO₂ oxy-fueled power cycle scope, technology, and the project design experience obtained via NET Power's demonstration facility in La Porte, TX. The study assumed a generic site, located near the U.S. Gulf Coast region. An indicative cost for the commercial plant was generated. The commercial development team has continued to optimize the design development to reduce commercial plant capital cost and program risks. The timing and schedule for finalization of this optimization is targeted to be in sync with the result of a commercial plant COD in 2021.

The base commercial plant design uses natural gas as fuel and oxygen from an on-site air separation unit (ASU) to reliably produce electricity and carbon dioxide (CO₂) for local pipeline export to downstream consumers such as enhanced oil recovery (EOR) operations. Under normal operation, the plant does not emit CO₂ into the atmosphere or any other emissions.

The CO₂ recuperative heat exchangers and the combustion turbine generator (CTG) are the key pieces of equipment for the plant. Toshiba is currently developing the design of the commercial scale CTG utilizing lessons learned from the 50 MWth Demonstration Plant. The design of the recuperative heat exchanger train optimizes heat recovery for the required extreme temperature and pressure conditions demonstrating existing technology but in a first-of-a-kind regime of coincident pressure and temperature.

5. CO₂ Uses – A Review of Emerging Opportunities

The market potential for CO₂ products is coming into focus. The Global CO₂ Initiative and CO₂ Sciences have estimated that by 2030, CO₂ products could generate between \$800 billion and \$1.2 trillion annually and reduce CO₂ emissions by 10% to 15% [5].

There is increased interest in finding non-injection based uses for CO₂, which is exemplified by the \$20 million NRG/COSIA Carbon X-Prize that is aimed at scaling CO₂ utilization applications and is currently underway. Existing uses for CO₂, which have been in commercial practice for decades, include the production of urea, methanol, carbonate salts, polycarbonates, and other specialty chemicals (including carbon nanotubes).

Recently, methods for curing cement/concrete have deployed commercially. Companies deploying these technologies include Solidia, CarbonCure, Carcrete, and Carbon Upcycling. There are also other technologies in development for converting ethane to ethylene using CO₂ as a soft oxidant.

Conversion of CO₂ to specialty chemicals is attractive due to the high-margins, but the total CO₂ consumed is low relative to EOR. These high-margins provide a near-term financial justification/incentive for the build out of the required CO₂ transportation infrastructure. On the other hand the volume of CO₂ consumed for processes like fuel production and aggregates (e.g. cement) offset higher margins with larger volumes. It is predicted that high volume applications will become market drivers. Indeed, a recently released study predicted that the markets for concrete and aggregates (\$165B - \$550B) and fuels (\$10B - \$250B) would likely dwarf that of chemicals (\$1B - \$12B) by 2050. This may speak to more insight and/or optimism into those subsectors by respondents who have some stake in it [5].

Use of CO₂ as the feedstock for plastics and polymers productions processes is another attractive application. One example is US-based Novomer, a company that converts CO₂ to polycarbonates/polyols, which initially received investment from Saudi Aramco. Additionally, German polymer company, Covestro, is already using CO₂ in the production of foams used in mattresses and upholstered furniture and is planning to expand its production lines of CO₂-feedstock-based polyols. Perhaps the most interesting application lies in “new materials,” including the likes of carbon fiber, carbon nanotubes, and carbon-based nanoparticles.

Nevertheless, an even larger opportunity may exist to support further CCUS and associated innovation. 8 Rivers is exploring a whole host of applications where cryogenic CO₂ separation can be exploited to create more cost effective energy resources, with CO₂ provided by a NET Power facility or other source of captured high pressure carbon dioxide.

6. The Many Uses of Cryogenic CO₂ Enables a New Energy Portfolio

6.1. TarT Process for Natural Gas Sweetening

A significant portion of natural gas reserves around the world contain large quantities of sulfur species and carbon dioxide, which are often referred to as sour gas reservoirs. The IEA reports that more than 40% of the world's gas reserves outside of North America are sour, with the number increasing to 60% for Middle Eastern gas reserves [6] [7]. Sulfur species, such as hydrogen sulfide (H₂S), are highly corrosive when mixed with water and toxic to biological organisms. In addition, the CO₂ has a negative effect on energy content of natural gas and increases the greenhouse gas emissions upon the usage of such natural gas source. In order to meet pipeline quality standards, natural gas is usually required to contain no more than 2% CO₂ and 4 ppm_v H₂S on a volume basis. The process of removing acid gases from the natural gas, also called gas sweetening, is traditionally carried out using commercial solvents such as MEA, MDEA and Selexol based on their composition and the amount of acid gases to be removed. Putting the environmental impact of such solvents aside, high concentrations of acid gases (e.g. >20% H₂S+CO₂) tend to increase the capital and operating costs of natural gas sweetening processes, which would make the economic utilization of such acid gas reserves difficult.

Cryogenic separation of acid gases from natural gas can be a cost effective alternative to conventional acid gas removal processes, especially in the presence of large quantities of acid gases. 8 Rivers' TarT™ liquid CO₂ scrubbing process is a new technology that exploits cryogenic separation and thermo-physical properties of liquid CO₂ for natural gas sweetening. A simplified block flow diagram of the TarT process for natural gas sweetening is shown in Figure 3.

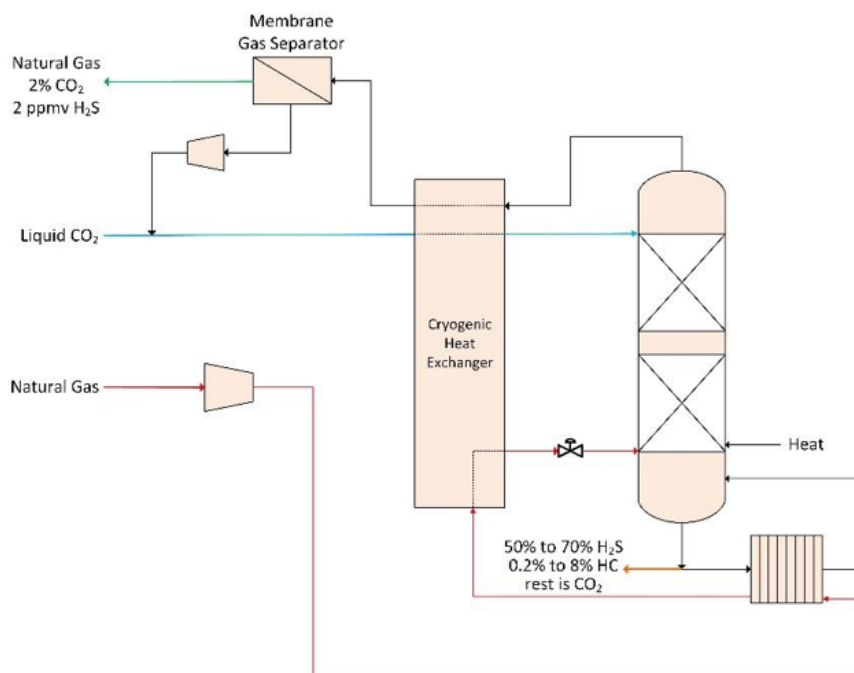


Figure 3. Block flow diagram of TarT process for sweetening of sour gas

The TarT process relies on the use of liquid CO₂ as a solvent to efficiently scrub the H₂S out of sour gas. A simple packed distillation column with rectifying and stripping zones is at the heart of the TarT process. Liquid CO₂ and sour gas are cooled to a temperature near CO₂ triple point (-56.6 °C) and then are introduced into the top and bottom sections of the column, respectively. Operation of the column above the triple point of CO₂ avoids solidification of CO₂ within the column and connecting pipes at any operational conditions and thus the need for an advanced and complex column design such as that used in the Controlled Free Zone ® (CFZ ®) process. The bottom liquid product from the distillation column contains nearly all H₂S within the sour gas feed as well as some CO₂ and hydrocarbons. The removal rate of H₂S from the column can be tuned by controlling the flow rate of fresh makeup CO₂ fed into the column. Clean natural gas leaving the top of the column is processed in a membrane separation unit to achieve desired CO₂ content in the final clean gas product, and the CO₂ on the permeate side of the membrane will be compressed and recycled back to the system. Meeting the pipeline requirements for CO₂ content (<2% volume) can be achieved using a single stage commercial membrane systems for CO₂ removal. The sour residue collected at the bottom of column is in liquid phase, which facilitates its pumping for reinjection operations. Alternatively, it can be readily used as a feedstock in Claus process for sulfur production.

Table 3. Overall performance of the TarT process for sweetening of two highly sour natural gas compositions.

Sour gas composition	72% CH ₄ , 18% H ₂ S, 10% CO ₂	72% CH ₄ , 10% H ₂ S, 18% CO ₂
CH ₄ content within sour feed (kmol/hr)	5760	5760
Total parasitic load (MW)	17.88	19.56
Makeup CO ₂ (tonne/day)	210.14	256.5
Specific parasitic load (kWh/kmol-H ₂ S removed)	12.42	24.45
Specific parasitic load (kWh/kmol-H ₂ S + CO ₂ removed)	8.40	9.20
Heat/steam input (MW)	0	0
CH ₄ lost in the bottom product (% of total CH ₄ input)	4.0	4.0
Clean gas composition (% CO ₂ , ppmv H ₂ S)	2, 2	2, 2

Table 3 shows the overall mass and energy balance of the TarT process for sweetening of two highly sour natural gas feedstock. Once integrated with a process that relies on natural gas feedstock and equipped with CO₂ capture, the TarT process can utilize by-product CO₂ to generate low-cost pipeline quality gas that can substantially improve the economics of the downstream process.

6.2. Solid Fuel Allam Cycle

In addition to burning natural gas, the Allam Cycle can be applied to coal syngas power generation by integrating with a commercially proven coal gasification system, where it is projected to make major efficiency gains and capital cost reductions over conventional coal systems while still realize full carbon capture [3] [8]. To address the specific challenges for the coal-based Allam cycle, including gasifier selection and integration, materials corrosion, syngas impurities removal, and design of a high-pressure oxy-fired syngas combustor, 8 Rivers has worked with the Energy & Environmental Research Center (EERC) and the North Dakota Industrial Commission (NDIC) Lignite Energy Council (LEC) on a lignite-based Allam Cycle technology development program in support of an industry team comprising ALLETE, Inc., and Basin Electric Power Cooperative (BEPC). In parallel, 8 Rivers has developed a proprietary fuel flexible sCO₂ combustor for the coal syngas Allam Cycle [9]. Current highlights of coal the Allam Cycle research program include the following activities:

- A detailed gasifier selection study was completed to investigate suitable gasifiers for the Allam Cycle. The results show that both entrained flow gasifiers and fluidized bed gasifiers provide good economics across a wide range of fuel types. A detailed feasibility study showed that the Allam Cycle coal system provides significant cost of electricity advantage compared to IGCC/SCPC.
- The initial design of a fuel flexible combustor and test rig were completed. A CFD simulation was conducted to validate the feasibility of multi-fuel operation. The CFD results show that the combustor can achieve designed combustor exit temperature and pressure, as well as a complete fuel burnout [10].
- Two 1500 hour dynamic corrosion tests under 30 bar (435 psi) / 750°C (1382°F) and 269 bar (3902 psi) / 750°C (1382°F) were completed. The test gas at 30 bar (435 psi) / 750°C (1382°F) was simulated to represent a typical combustion flue gas in the coal based Allam Cycle with amine-based pre-combustion

sulfur removal. Test gas at 269 bar (3902 psi) / 750°C (1382°F) represented the oxidant stream in the coal based Allam Cycle. The corrosion mechanisms and rates from the tests did not present any barriers to uses of any high nickel alloys under consideration in the coal based Allam Cycle.

- A patented post-combustion sulfur removal concept was tested and demonstrated with the sulfur removal rate of over 99% [11].

Additionally, 8 Rivers has begun to evaluate a modified version of the TarT natural gas scrubbing process for use with syngas. Initial results are promising and show that cryogenically washing H₂S containing syngas with CO₂ derived from the Allam Cycle may serve as a low-cost alternative to conventional pre-combustion sulfur removal systems often used in gasification trains. Furthermore, the liquid scrubber effluent of CO₂ and H₂S is capable of further processing via conventional Claus plant tail gas cleanup systems to produce pipeline quality CO₂ and elementary sulfur.

6.3. TarT Process for Sour Gas Combustion

8 Rivers developed a novel method which enables sour natural gas as well as the liquid effluent from the TarT process for natural gas sweetening to be directly burned for power generation without any pretreatment. This method can potentially reduce the cost of power production using sour gas feedstock products by eliminating the natural gas pretreatment steps. Oxidized sulfur compounds are captured by limestone in the combustion process to eliminate downstream sulfur corrosion. The desulfurized flue gas then goes through a solids removal process before entering a gas turbine or a turbine expander for power generation. A steam cycle is used for waste heat recuperation from both the turbine exhaust stream and the solids stream to improve the cycle performance. Both air-combustion (see Figure 4) and oxy-combustion configurations (see Figure 5) were investigated and modeled using Aspen Plus.

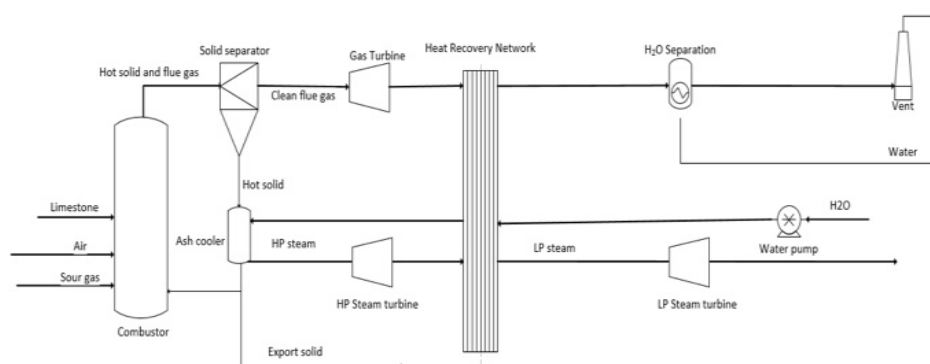


Figure 4. Flow diagram of air-combustion sour gas cycle

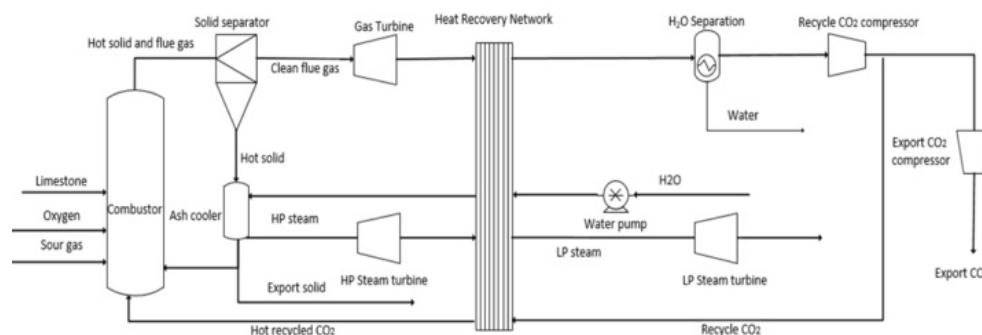


Figure 5. Flow diagram of oxy-combustion sour gas cycle with carbon capture

The design conditions of each cycle are within the operating envelope of commercially available equipment, including compressors, turbines and heat exchangers, enabling near-term deployment of the proposed system. The result of process modeling using ASPEN Plus shows that overall thermal efficiency in a 40-50% range (LHV basis) are achievable using this approach. Without pretreatment, the heating value of sulfur in the sour gas and the heat released from the limestone scrubbing process can be fully utilized for power generation, thus improving the cycle performance. Lu, et al. have completed a detailed techno-economic analysis of the sour gas combustion system. The economic analysis estimates that a baseline air-combustion sour gas system is 41% cheaper than NGCC in 2011, and about 28% cheaper than advanced NGCC in 2022 on a simplified Levelized Cost of Electricity (LCOE) basis. The LCOE of the oxy-combustion sour gas system is estimated to be 53% lower than advanced NGCC in 2022 when the revenue from CO₂ and Argon sales are taken into account. The Capex estimation of the sour gas combustion system is based on the cost of a commercial scale Pressurized Fluidized bed Combustion (PFBC) coal system in 2018 U.S. dollars. This is a conservative approach since the capital costs associated with coal grinding/handling, ash treatment/disposal, and other coal related processes are eliminated in the sour gas power system. Therefore, the novel untreated sour gas combustion system presented suggests that the petroleum and power industries have an opportunity to use sour gas for power generation efficiently, cost effectively and potentially with full carbon capture [12].

6.4. Carbon Free Hydrogen

Large scale hydrogen generation is traditionally carried out using steam-methane reforming process as shown in Figure 6.

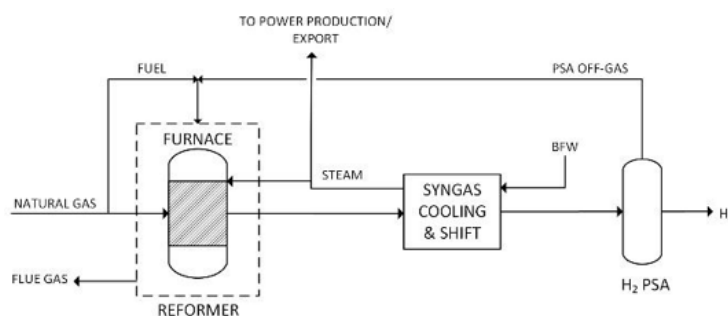


Figure 6: simplified block flow diagram of steam methane reforming process

The SMR process has a relatively high CO₂ footprint of around of 916 kg-CO₂/kNm³-H₂ [13]. The most effective method to substantially reduce the carbon footprint of such a process is to capture CO₂ from the reformer flue gas using conventional systems. The flue gas from reformer furnace is at near atmospheric pressure, which will require a large absorption tower and other associated equipment. In addition, the recovery of solvent requires a relatively large amount of heat in the form of heat that significantly reduces overall hydrogen generation efficiency. A recent study suggests that using a solvent-based CO₂ capture unit to achieve an overall CO₂ capture rate of 90% in an SMR process would increase the levelized cost of hydrogen by about 45%.

An alternative method of hydrogen generation is the use of a two-stage high pressure syngas generation system utilizing a combination of partial oxidation and steam methane reforming reactors. In such a scheme, the former is utilized to generate heat (and syngas of lower quality) while the latter is to generate high quality syngas using the heat generated in the partial oxidation step. In this way, all CO₂ generated due to the reforming reactions is contained within the high pressure syngas loop which makes the downstream separation of CO₂ more facile. A simplified block flow diagram of a hydrogen generation process using the alternative method, which is referred to as 8RH2 is shown in Figure 7.

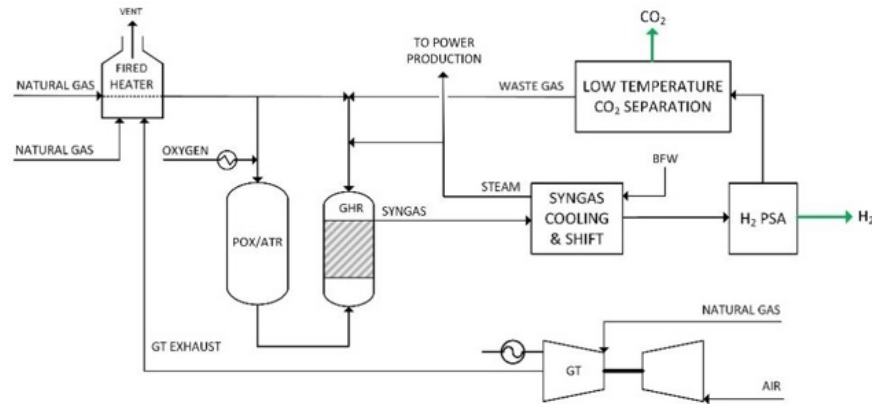


Figure 7: Simplified block flow diagram of 8RH2 process for hydrogen generation with carbon capture

In the combined reforming concept, natural gas is partially oxidized in an oxygen deficient environment. In catalytic variation of partial oxidation, also known as auto-thermal reforming (ATR), the product gas from the partial oxidation section of the reactor is passed through a catalyst bed to enhance syngas generation reactions. The product gas from the first step, is directed to a heat exchanger reformer, also called gas heated reformer (GHR), which is essentially a conventional reformer without the burner and furnace section. The hot product gas at 1050-1400 C (depending on the type of partial oxidation reactor used) drives the steam methane reforming reactions within the GHR tubes, and eventually both syngas streams combine to form the main syngas stream at 550-600 C. After syngas shifting and cooling steps and hydrogen separation, the PSA waste gas contains about 76% CO₂ (mole basis) which is suitable for processing in a low temperature removal system. Such a system uses the auto-refrigeration principle to cool down the process stream near CO₂ triple point, and separates and purifies CO₂ product in a distillation column. 8 Rivers' proprietary low temperature CO₂ removal system captures CO₂ at 150 bar and 99%+ (mole basis) purity by only using electrical energy at 200-220 kWh/tonne-CO₂. The residual gas from CO₂ separation system can be recycled back to the reforming reactors to maximize the process efficiency and CO₂ capture.

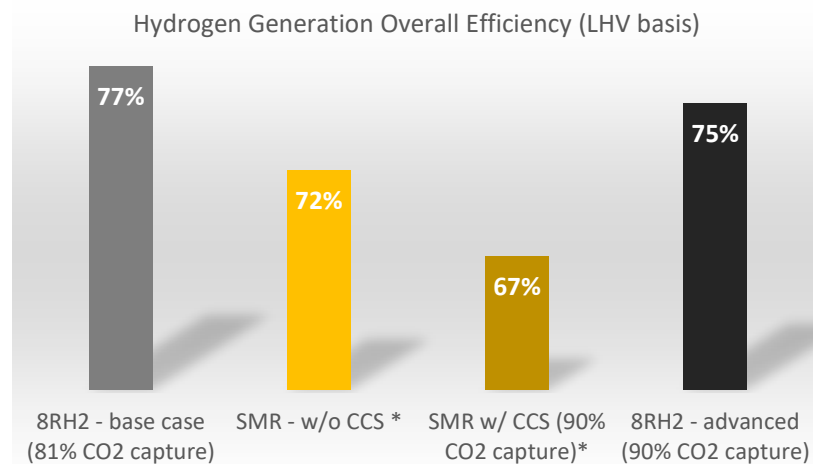


Figure 8. Comparison of overall thermodynamic efficiency of the 8RH2 process and a conventional steam methane reforming process with and without carbon capture.

*SMR process figures were taken from [13]. SMR with CCS removes CO₂ from SMR furnace flue gas using Shell Cansolv process.

Due to the use high purity oxygen and relatively higher electricity consumption in the combined reforming method, additional electricity will be required that can be drawn from the grid or provided using on-site gas turbine. The latter would allow more efficient heat integration within the process at the expense of CO₂ emission due to firing in the gas turbine. In this process as depicted in Figure 7, about 81% of process overall CO₂ is captured. Up to 100% CO₂ captured can be achieved by partially or completely replacing the gas turbine fuel with a portion of hydrogen product from the process. A comparison of the overall thermodynamic efficiency of 8RH2 and a conventional steam methane reforming process is shown in Figure 8.

7. Conclusions

Progress at NET Power continues to move forward. The NET Power demonstration facility is nearing full proof-of-concept following successful testing of the combustor. In tandem, the commercial design of a NET Power facility continues to be progressed. The Allam Cycle, developed with the aim of producing power at a cost competitive with existing best-in-class, non-carbon capture power generation technologies while capturing all emissions for no additional cost is inspiring work in other areas. 8 Rivers has applied the same approach to adjacent and related markets, generating new innovative clean energy processes. Work on novel CO₂ uses, fuel clean-up, combustion, and hydrogen production technologies has taken place, with an overview of that work provided in this paper.

8. Acknowledgements

We would like to thank our team members at 8 Rivers who have supported this work, as well as our partners Exelon Corporation and McDermott International and our technology developer Toshiba Corporation for their tireless contributions.

References

- [1] R. J. Allam, M. R. Palmer, G. W. Brown, J. Fetvedt, D. Freed, H. Nomoto, M. Itoh, N. Okita and C. Jones, "High Efficiency and Low Cost of Electricity Generation from Fossil Fuels While Eliminating Atmospheric Emissions, Including Carbon Dioxide," *Energy Procedia*, vol. 37, pp. 1135-1149, 2013.
- [2] R. Allam, S. Martin, B. Forrest, J. Fetvedt, X. Lu, D. Freed, G. W. Brown, T. Sasaki, M. Itoh and J. Manning, "Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture," *Energy Procedia*, vol. 114, pp. 5948-5966, 2017.
- [3] X. Lu, B. Forrest, S. Martin, J. Fetvedt, M. McGroddy and D. Freed, *Integration and Optimization of Coal Gasification Systems with a Near-Zero Emissions Supercritical Carbon Dioxide Power Cycle*, 2016.
- [4] T. Sasaki, M. Itoh, H. Maeda, J. Tominaga, D. Saito and Y. Niizeki, *Development of Turbine and Combustor for a Semi-Closed Recuperated Brayton Cycle of Supercritical Carbon Dioxide*, 2017.
- [5] C. S. Initiative and C. The Global, *Global Roadmap for Implementing CO2 Utilization*, 2016.
- [6] International Energy Agency, "Natural Gas Resources and Production Prospects," in *World Energy Outlook*, Paris, Organisation for Economic Co-operation and Development, 2008, p. 283.
- [7] W. F. J. Burgers, P. S. Northrop, H. S. Kheshgi and J. A. Valencia, "Worldwide development potential for sour gas," *Energy Procedia*, vol. 4, pp. 2178-2184, 11 2011.
- [8] J. D. Laumb, M. J. Holmes, J. J. Stanislawski, X. Lu, B. Forrest and M. McGroddy, "Supercritical CO2 Cycles for Power Production," *Energy Procedia*, vol. 114, pp. 573-580, 2017.
- [9] J. Fetvedt, *Coal Syngas Combustor Development for High-Pressure, Oxy-Fuel SC02 Cycle Applications*, 2014.
- [10] H. Abdul-Sater, J. Lenertz, C. Bonilha, X. Lu and J. Fetvedt, *A CFD Simulation of Coal Syngas Oxy-Combustion In a High-Pressure Supercritical CO2 Environment*, 2017.
- [11] X. Lu, S. Martin, M. McGroddy, M. Swanson, J. Stanislawski and J. Laumb, "Testing of a Novel Post Combustion Acid Removal Process for the Direct-Fired, Oxy-Combustion Allam Cycle Power Generation System," *Journal of Engineering for Gas Turbines and Power*, 2017.
- [12] M. P. B. F. M. M. Xijia Lu, A Novel Power Generation System Utilizing Un-treated Sour Gas Fuel, "SPE-192823-MS, ABU DHABI INTERNATIONAL PETROLEUM EXHIBITION & CONFERENCE 12-15 NOVEMBER, , 2018.
- [13] G. Collodi, G. Azzaro, N. Ferrari and S. Santos, "Techno-economic Evaluation of Deploying CCS in SMR Based Merchant H2 Production with NG as Feedstock and Fuel," *Energy Procedia*, vol. 114, pp. 2690-2712, 2017.

EXHIBIT MARTIN03

To Declaration of June Ann Munford



Items ▾

Search for books, articles, and more

[Create account](#)[Sign in](#)[Home](#) [Libraries](#) [Topics](#) [Lists](#) [About](#) [For Librarians](#)[Pittsburgh, Pennsylvania, US](#) ▾

Progress Update on the Allam Cycle: Commercialization of Net Power and the Net Power Demonstration Facility

Authors: [Scott Martin](#), [Brock Forrest](#), [Navid Rafati](#), [Xijia Lu](#), [Jeremy Fetvedt](#), [Mike McGroddy](#), [Bill Brown](#), [Rodney Allam](#), [Damian Beauchamp](#), [David Freed](#)

Article, 2019

Edition: [View all formats and editions](#)

Publication: SSRN Electronic Journal, 2019

DOI: [10.2139/ssrn.3366370](https://doi.org/10.2139/ssrn.3366370)

OLC Number / Unique Identifier: 8686834534

Language Notes: English

More Information: dx.doi.org

[Show less information](#) ^

Borrow from **Library of Congress** near
Pittsburgh, Pennsylvania

[Borrow](#)

185 miles away

Find a Copy at a Library

Filter by: [Any format](#) ▾ [Any edition](#) ▾ [Distance within 200+ mi](#) ▾

[Featured libraries](#)

[All libraries](#)

Showing 98 libraries near [Pittsburgh, Pennsylvania](#)

☐ Only public libraries



Library of Congress

[Borrow](#)

[185 miles](#) from your current location.
101 Independence Avenue, SE, Washington, DC, 20540, United States



University of Rochester

[Borrow](#)

[216 miles](#) from your current location.
Rush Rhees Library, 755 Library Road, Rochester, NY, 14627-0011, United States



Cornell University Library

[Borrow](#)

[220 miles](#) from your current location.
201 Olin Library, Ithaca, NY, 14853-5301, United States



Virginia Tech

Newman Library

[Borrow](#)

[225 miles](#) from your current location.
560 Drillfield Drive, Blacksburg, VA, 24061, United States



Villanova University

Falvey Library

[Borrow](#)



Academic

[238 miles](#) from your current location.
Falvey Library, 800 Lancaster Avenue, Villanova, PA, 19085, United States



Academic

Haverford College Library

[240 miles](#) from your current location.
370 Lancaster Avenue, Haverford, PA, 19041-1392, United States

Borrow



Law

University of Pennsylvania Biddle Law Library

Biddle Law Library
 [246 miles](#) from your current location.
Biddle Law Library, 3460 Chestnut St, Philadelphia, PA, 19104, United States

Borrow



Academic

Syracuse University

[261 miles](#) from your current location.
222 Waverly Avenue, Suite 219 - Administration, Syracuse, NY, 13244-2010, United States

Borrow



Academic

Princeton University Library

Firestone Library
 [271 miles](#) from your current location.
1 Washington Rd, Princeton, NJ, 08544-2098, United States

Borrow



Law

Cooley Law School

[291 miles](#) from your current location.
300 South Capitol Avenue, Lansing, MI, 48933, United States

Borrow



Academic

New York Law School Library

Mendik Law Library
 [305 miles](#) from your current location.
185 W. Broadway, New York, NY, 10013, United States

Borrow



Academic

New York University Law School Library

[306 miles](#) from your current location.
40 Washington Sq S, Rm 102, New York, NY, 10012-1099, United States

Borrow



Academic

The Cooper Union Library

Cooper Union Library
 [306 miles](#) from your current location.
7 East 7th St., Ground floor, New York, NY, 10003-7120, United States

Borrow



Academic

Brooklyn Law School

[306 miles](#) from your current location.
Library, 250 Joralemon St, Brooklyn, NY, 11201, United States

Borrow



Columbia University in the City of New York

Borrow



Academic

Columbia University Libraries



[308 miles](#) from your current location.

535 West 114th Street, New York, NY, 10027-7035, United States



Favorite
Library



Academic

Duke University, Law Library

J. Michael Goodson Law Library



[312 miles](#) from your current location.

210 Science Dr., Box 90361, Durham, NC, 27708, United States



Favorite
Library



Academic

North Carolina Central University

Law School Library



[314 miles](#) from your current location.

Turner Law Bldg, 640 Nelson Street, Durham, NC, 27707, United States



Favorite
Library



Academic

University of North Carolina at Chapel Hill. Kathrine R. Everett Law Library

Kathrine R. Everett Law Library



[317 miles](#) from your current location.

160 Ridge Road, Chapel Hill, NC, 27599-3385, United States



Favorite
Library



Academic

North Carolina State University

NC State University Libraries



[327 miles](#) from your current location.

2 Broughton Dr., Campus Box 7111, Raleigh, NC, 27695-7111, United States



Favorite
Library



Academic

University of Notre Dame

Hesburgh Library



[345 miles](#) from your current location.

150 Hesburgh Library, Notre Dame, IN, 46556-5629, United States



Favorite
Library



Academic

Indiana University Southeast

IU Southeast; IUS; IUSE



[353 miles](#) from your current location.

4201 Grant Line Road, IU Southeast Library, New Albany, IN, 47150, United States



Favorite
Library



Academic

University of Tennessee College of Law

Joel A. Katz Law Library



[383 miles](#) from your current location.

1505 W Cumberland Ave, Knoxville, TN, 37996, United States



Favorite
Library



Academic

University of Tennessee at Knoxville

John C. Hodges Library



[383 miles](#) from your current location.

1015 Volunteer Boulevard, 306 Hodges Libr, Knoxville, TN, 37996-1000, United States



Favorite
Library



Academic

Amherst College Library

Frost Library



[401 miles](#) from your current location.

61 Quadrangle Dr, Amherst, MA, 01002, United States



Favorite
Library



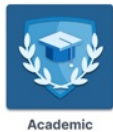
Supreme Court of Canada, Library, Ottawa

Cour suprême du Canada, Bibliothèque, Ottawa

Borrow



[401 miles](#) from your current location.
301 Wellington Street, Ottawa, ON, K1A 0J1, Canada



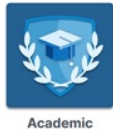
Catholic Theological Union

Paul Bechtold Library

Borrow



[415 miles](#) from your current location.
Paul Bechtold Library, 5416 South Cornell Avenue, Chicago, IL, 60615-5698, United States

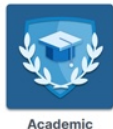


University of Chicago Library

Borrow



[415 miles](#) from your current location.
1100 E. 57th Street, Chicago, IL, 60637, United States



Chicago-Kent College of Law

Chicago-Kent College of Law Library

Borrow



[419 miles](#) from your current location.
565 West Adams Street, Chicago, IL, 60661-3691, United States

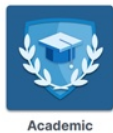


Northwestern University

Borrow



[423 miles](#) from your current location.
Library-III Department, 1970 Campus Drive, Evanston, IL, 60208-2300, United States



University of Illinois at Urbana Champaign

Borrow



[444 miles](#) from your current location.
1408 W Gregory Dr, 128 Main Libr Mc 522, Urbana, IL, 61801-3692, United States



Boston College, Law Library

Borrow



[465 miles](#) from your current location.
885 Centre St, Newton, MA, 02459-1100, United States



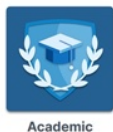
Boston College

Thomas P. O'Neill Library

Borrow



[466 miles](#) from your current location.
140 Commonwealth Avenue, Chestnut Hill, MA, 02467, United States



Boston University Libraries

Mugar Memorial Library

Borrow



[470 miles](#) from your current location.
Mugar Mem Libr, 771 Commonwealth Ave, Boston, MA, 02215-1401, United States



Tufts University - Tisch Library

Tisch Library

Borrow



[470 miles](#) from your current location.

Academic Tisch Libr, 35 Professors Row, Medford, MA, 02155, United States



Academic

MIT Libraries

Massachusetts Institute of Technology Libraries

 [470 miles](#) from your current location.
77 Massachusetts Ave., Cambridge, MA, 02139, United States

Borrow 



Favorite Library



Academic

Salem State University

 [482 miles](#) from your current location.
Frederick E. Berry Library, 352 Lafayette St., Salem, MA, 01970, United States

Borrow 



Favorite Library



Academic

Washington University in St. Louis

 [572 miles](#) from your current location.
1 Brookings Drive, MSC 1061-141-B, St. Louis, MO, 63130, United States

Borrow 



Favorite Library



Academic

Hamline University Library

Bush Memorial Library
 [745 miles](#) from your current location.
1536 Hewitt Ave., Ms-C1919, St. Paul, MN, 55104, United States

Borrow 



Favorite Library



Academic

University of Kansas

KU Library
 [826 miles](#) from your current location.
1425 Jayhawk Boulevard, Lawrence, KS, 66045-7547, United States

Borrow 



Favorite Library



Academic

University of Manitoba Libraries

 [1,059 miles](#) from your current location.
Elizabeth Dafoe Library, Directors Office, Winnipeg, MB, R3T 2N2, Canada

Borrow 



Favorite Library



Academic

University of North Texas Library

UNT
 [1,079 miles](#) from your current location.
University Libraries, 1155 Union Circle #305190, Denton, TX, 76203-5190, United States

Borrow 



Favorite Library



Academic

Midwestern State University

Moffett Library
 [1,123 miles](#) from your current location.
Midwestern State University, 3410 Taft Blvd, Wichita Falls, TX, 76308-2099, United States

Borrow 



Favorite Library



Academic

Baylor University Libraries

Moody Memorial Library
 [1,143 miles](#) from your current location.
1312 S 3rd St., Waco, TX, 76798-7143, United States

Borrow 



Favorite Library



Minot State University, Gordon B Olson Library

Gordon B. Olson Library

Borrow 



1,185 miles from your current location.

500 University Avenue West, Minot, ND, 58707, United States

 Favorite Library



Colorado State University
Morgan Library

1,322 miles from your current location.

1019 Campus Delivery, Ft Collins, CO, 80523-1019, United States

 Favorite Library



Memorial University of Newfoundland- QEII Library
Memorial University of Newfoundland- QEII Library

1,424 miles from your current location.

Queen Elizabeth II Library, 234 Elizabeth Avenue, St Johns, NL, A1B 3Y1, Canada

 Favorite Library



Brigham Young University-Idaho
David O. McKay Library

1,644 miles from your current location.

525 South Center Street, Rexburg, ID, 83460-0405, United States

 Favorite Library



Southern Utah University
Gerald R. Sherratt Library

1,784 miles from your current location.

351 W University Blvd, Cedar City, UT, 84720, United States

 Favorite Library



Washington State University - Spokane
WSU Health Sciences Library

1,911 miles from your current location.

WSU Health Sciences Library, 600 North Riverpoint Boulevard, Room 200, Spokane, WA, 99202, United States

 Favorite Library



Washington State University, Tri-Cities Campus

2,000 miles from your current location.

2770 Crimson Way, Richland, WA, 99354-1671, United States

 Favorite Library

<
1
2
>

Results per Page: 50 ▼



WorldCat is the world's largest library catalog, helping you find library materials online.

Language

English ▼

[Copyright © 2001-2024 OCLC. All rights reserved.](#)
[Terms and Conditions](#) [Help](#)

[© 2024 OCLC Domestic and international trademarks and/or service marks of OCLC, Inc. and its affiliates.](#) [Cookie notice](#) [Manage my cookies](#)

Home Libraries Topics Lists

About For Librarians Help & FAQ Contact Us






[Privacy Policy](#) [Accessibility Statement](#) [ISO 27001 Certificate](#)



Items ▾

Search for books, articles, and more

[Create account](#)[Sign in](#)[Home](#) [Libraries](#) [Topics](#) [Lists](#) [About](#) [For Librarians](#)[Pittsburgh, Pennsylvania, US](#) ▾

Progress Update on the Allam Cycle: Commercialization of Net Power and the Net Power Demonstration Facility

Authors: [Scott Martin](#), [Brock Forrest](#), [Navid Rafati](#), [Xijia Lu](#), [Jeremy Fetvedt](#), [Mike McGroddy](#), [Bill Brown](#), [Rodney Allam](#), [Damian Beauchamp](#), [David Freed](#)

Article, 2019

Edition: [View all formats and editions](#)

[Show more information](#) ▾

Borrow from **University of San Diego**
near Pittsburgh, Pennsylvania

[Borrow](#)

2,123 miles away

Find a Copy at a Library

Filter by: [Any format](#) ▾ [Any edition](#) ▾ [Distance within 200+ mi](#) ▾

Featured libraries

[All libraries](#)

Showing 83 libraries near [Pittsburgh, Pennsylvania](#)

☐ Only public libraries



Academic

University of San Diego

Copley Library

[2,123 miles](#) from your current location.
5998 Alcalá Park, San Diego, CA, 92110-2492, United States

[Borrow](#)



Public

King County Library System

Service Center, Administrative Offices

[2,127 miles](#) from your current location.
960 Newport Way NW, Issaquah, WA, 98027, United States

[Borrow](#)



Academic

University of California, Irvine

Langson Library

[2,132 miles](#) from your current location.
Univ of California Irvine, Irvine, CA, 92697, United States

[Borrow](#)



Law

University of Washington Gallagher Law Library

Marian Gould Gallagher Law Library

[2,139 miles](#) from your current location.
William H. Gates Hall, 4000 15th Avenue NE, Seattle, WA, 98195-3020, United States

[Borrow](#)



Public

Seattle Public Library

Central Library

[2,140 miles](#) from your current location.
1000 Fourth Avenue, Seattle, WA, 98104, United States

[Borrow](#)



University of California, Los Angeles

[2,151 miles](#) from your current location.
280 Charles E. Young Dr., Los Angeles, CA, 90255, United States

[Borrow](#)





Academic

Washington State University, Vancouver Campus Library

WSU Vancouver Library

[2,164 miles](#) from your current location.

14204 NE Salmon Creek Avenue, Vancouver, WA, 98686-9600, United States

Borrow



Favorite Library



Academic

University of California, Merced

UC Merced Library

[2,174 miles](#) from your current location.

Leo & Dottie Kolligian Library, 5200 N Lake Road, Merced, CA, 95343, United States

Borrow



Favorite Library



Academic

University of Oregon Libraries

UO Libraries

[2,200 miles](#) from your current location.

1501 Kincaid Street, 1299 University of Oregon, Eugene, OR, 97403-1299, United States

Borrow



Favorite Library



Law

University of Oregon Libraries

John E. Jaqua Law Library

[2,200 miles](#) from your current location.

1515 Agate Street, Eugene, OR, 97403-1221, United States

Borrow



Favorite Library



Academic

Stanford University Law School

Robert Crown Law Library

[2,264 miles](#) from your current location.

Robert Crown Law Library, 559 Nathan Abbott Way, Stanford, CA, 94305-8612, United States

Borrow



Favorite Library



Academic

University of Edinburgh - Main Library

Edinburgh University Library

[3,489 miles](#) from your current location.

George Square, Edinburgh, EH8 9LJ, United Kingdom

Borrow



Favorite Library



Academic

University of Sheffield

Sheffield University

[3,608 miles](#) from your current location.

University of Sheffield Library, Western Bank, Sheffield, S10 2TN, United Kingdom

Borrow



Favorite Library



Academic

University of Cambridge

Cambridge University Library

[3,699 miles](#) from your current location.

Cambridge University Library, West Road,, Cambridge, CB3 9DR, United Kingdom

Borrow



Favorite Library



Academic

UCL

University College London

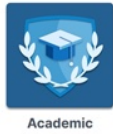
[3,706 miles](#) from your current location.

Gower Street,, London, WC1E 6BT, United Kingdom

Borrow



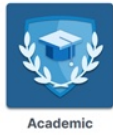
Favorite Library



IE University Library

 [3,867 miles](#) from your current location.
MARÍA DE MOLINA 31 BIS, Madrid, 28006, Spain

Borrow 

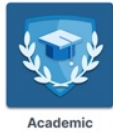


Erasmus University Rotterdam

University Library, Rotterdamsch Leeskabinet, ISS Library, EUC Library, Sanders Law Library, Medical Library

 [3,879 miles](#) from your current location.
Burgemeester Oudlaan 50, Rotterdam, 3062 PA, Netherlands

Borrow 

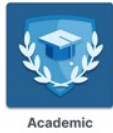


Universite Libre de Bruxelles - Bibliothèques

ULB

 [3,905 miles](#) from your current location.
Av. F.-D. Roosevelt, 50, Bruxelles, 1050, Belgium

Borrow 



Tilburg University Library

Universiteit van Tilburg, Bibliotheek

 [3,910 miles](#) from your current location.
Warandelaan 2, Tilburg, 5037 AB, Netherlands

Borrow 

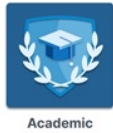


Eindhoven University of Technology

Eindhoven University of Technology

 [3,930 miles](#) from your current location.
Groene Loper 3, Eindhoven, 5612 AE, Netherlands

Borrow 



Maastricht University Library

Universiteit Maastricht

 [3,956 miles](#) from your current location.
Grote Looiersstraat 17, Maastricht, 6211 JH, Netherlands

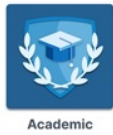
Borrow 



Universitätsbibliothek Kiel, Zentralbibliothek

 [4,018 miles](#) from your current location.
Leibnizstr. 9, Kiel, 24118, Germany

Borrow 



ZBW - Leibniz-Informationszentrum Wirtschaft, Kiel/Hamburg

 [4,019 miles](#) from your current location.
Düsternbrooker Weg 120, Kiel, 24105, Germany

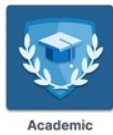
Borrow 



Helmut-Schmidt-Universität, Universität der Bundeswehr Hamburg, Universitätsbibliothek

 [4,041 miles](#) from your current location.
Holstenhofweg 85, Hamburg, 22043, Germany

Borrow 



Universidad de Alicante

Universitat d'Alacant

 [4,086 miles](#) from your current location.
Carretera San Vicente del Raspeig S/N, Alicante, 03690, Spain

Borrow 





Universitätsbibliothek Mannheim

[Borrow](#)

Academic

[4,108 miles](#) from your current location.
Schloss Schneckenhof, Mannheim, 68131, Germany



LIBRIS

[Borrow](#)

Library Network Group

[4,123 miles](#) from your current location.
Humlegårdsgatan 26, Box 5039, Stockholm, S-102 41, Sweden



Universitätsbibliothek Ilmenau

[Borrow](#)

Academic

[4,165 miles](#) from your current location.
Langewiesener Str. 37, Ilmenau, 98693, Germany



Universität Konstanz, Kommunikations-, Informations-, Medienzentrum (KIM)

[Borrow](#)

Academic

[4,197 miles](#) from your current location.
Universitätsstr. 10, Konstanz, 78464, Germany



Bayerische Staatsbibliothek

[Borrow](#)

Regional or National

[4,277 miles](#) from your current location.
Ludwigstr. 16, München, 80539, Germany



University of Hawaii at Manoa

[Borrow](#)

Academic

Hamilton Library
[4,662 miles](#) from your current location.
Hamilton Library, 2550 McCarthy Mall, Honolulu, HI, 96822, United States



Victoria University of Wellington, Kelburn Library

[Borrow](#)

Academic

VUW
[8,668 miles](#) from your current location.
Rankine Brown Building, 1 Kelburn Parade, Wellington, 6012, New Zealand



Singapore Management University

[Borrow](#)

Academic

[9,542 miles](#) from your current location.
70 Stamford Rd, Singapore, 178901, Singapore



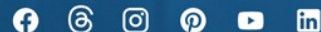
Results per Page: 50



WorldCat is the world's largest library catalog, helping you find library materials online.

[Home Libraries](#)

[About For Librarians](#)



Language

English

Topics
Lists

Help & FAQ
Contact Us



[Copyright © 2001-2024 OCLC. All rights reserved.](#)
[Terms and Conditions](#) [Help](#)

© 2024 OCLC. Domestic and international trademarks and/or service marks of OCLC,
Inc. and its affiliates. [Cookie notice](#) [Manage my cookies](#)

[Privacy Policy](#) [Accessibility Statement](#) [ISO 27001
Certificate](#)

EXHIBIT MARTIN04

To Declaration of June Ann Munford

Conference Paper

PDF Available

Supercritical CO₂ Demonstration Power Plant on Allam Cycle

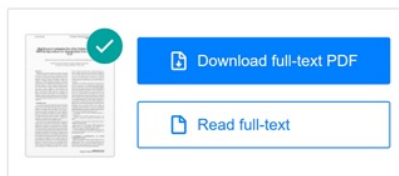
November 2019

Conference: International Gas Turbine Congress · At: Tokyo

Authors:



Parikshit Jain
University of California, Berkeley

[Download citation](#)[Copy link](#)

References (10)

Abstract

Toshiba Energy Systems & Solutions Corporation is developing a combustor and turbine for a novel power generation system that can capture CO₂ while generating power at high efficiency while using supercritical CO₂ (sCO₂) as working fluid. The combustor is designed to generate 1150degC and 30MPa at turbine inlet condition for a 50MWth demonstration plant. Direct combustion system generates sCO₂ combustion gas by high pressure oxy-fuel combustion method. To confirm combustion performance under sCO₂ environment and in order to validate the design, testing has been done at various conditions of inlet parameters. The experimental maximum conditions were about 90 bar and 900 degC at combustor exit conditions, and this is equivalent to the middle load condition of the turbine. This combustion test campaign covered from initial ignition to tested maximum load condition with good operation and performance, and we confirmed a successful combustion performance under sCO₂ environment of Allam cycle.

ResearchGate

Discover the world's research

- 25+ million members
- 160+ million publication pages
- 2.3+ billion citations

[Join for free](#)

Public Full-texts (4)

0232.pdf

Content uploaded by [Parikshit Jain](#)

Author content

Content may be subject to copyright.

IGTC-2019-232

Proceedings of the International Gas Turbine Congress 2019 Tokyo
November 17-22, 2019, Tokyo, Japan

High Pressure Combustion Test of Gas Turbine Combustor for 50MWth Supercritical CO₂ Demonstration Power Plant on Allam Cycle

Shinju Suzuki, Yasunori Iwai, Masao Itoh, Yuichi Morisawa, Parikshit Jain and Yoshihisa Kobayashi

Toshiba Energy Systems & Solutions Corporation, Keihin Product Operations
2-4, Suehiro-cho, Tsurumi-ku, Yokohama, 230-0045, Japan

ABSTRACT

Toshiba Energy Systems & Solutions Corporation is developing a combustor and turbine for a novel power generation system that can capture CO₂ while generating power at high efficiency while using supercritical CO₂ (sCO₂) as working fluid. The combustor is designed to generate 1150degC and 30MPa at turbine inlet condition for a 50MWth demonstration plant. Direct combustion system generates sCO₂ combustion gas by high pressure oxy-fuel combustion method. To confirm combustion performance under sCO₂ environment and in order to validate the design, testing has been done at various conditions of inlet parameters. The experimental maximum conditions were about 90 bar and 900 degC at combustor exit conditions, and this is equivalent to the middle load condition of the turbine. This combustion test

effective method of generating power, without discharging CO₂ outside. Echogen electric power system develops the supercritical CO₂ cycle which adopted the heater and the non-combustion system [2] and Sandia National Laboratories are advancing research on an efficient Brayton cycle by the supercritical CO₂ cycle using solar heat, a nuclear heat source, and a fossil fuel heat source [3].

Supercritical CO₂ turbine system (Allam Cycle) proposed by NET Power can collect CO₂ with high purity, without losing the energy by compression, and can attain high thermal efficiency (equivalent to the existing combined cycle plant) [4][5][6][7][8][9]. In this cycle, natural gas and oxygen reacts to CO₂ and H₂O in a combustor. The exhaust gas then drives a turbine with the mixed gas of CO₂ and H₂O which are combustion gas. After the

campaign covered from initial ignition to tested maximum load condition with good operation and performance, and we confirmed a successful combustion performance under sCO₂ environment of Allam cycle.

1. INTRODUCTION

As one of the measure to prevent global warming, the reduction of CO₂ emissions through thermal power plant is necessary. Increasing CO₂ emissions from thermal power plant has been a problem, the industrial shift from thermal power supply to renewable power supply is expanding. However, to keep stable grid control, the renewable power supply may require a backup by thermal power generation, in which new construction opportunities are limited. Hence thermal power supply is counterpart of renewable power supply and the research and development for reducing CO₂ emissions have been continued as well.

One of the direction is increasing thermal efficiency, such as the combined cycle of gas turbine and steam turbine configuration, which results in a reduce fuel use, and can reduce CO₂ emissions. Furthermore, development of a more advanced cycle of unifying SOFC (solid-oxide fuel cell) and combined cycle power generation is carried out, and this is called the "triple combined cycle" which may improve thermal efficiency greatly [1]. CCS (carbon recovery and storage) is separating CO₂ in a combustion exhaust gas with a chemical method, and is one of the technology which reduces the CO₂ emissions from a thermal power plant. However, the energy for carrying out scavenging of CO₂ is required, therefore the thermal efficiency of a plant goes down. In order to transport CO₂ collected by this system and to use for commercial benefit, application of pressure is needed. This pressurization process requires large energy. Application of the supercritical CO₂ closed-cycle technology to a thermal power plant is one of the most

combustion gas that carried out turbine driving passes a recuperator, H₂O is separated, and it is compressed with a compressor, and part of CO₂ is separated and collected. After the temperature increase of the remaining combustion gas is carried out by a recuperator, it is again supplied to a combustor. This cycle enables realization of an ideal near-zero-emission power-plant system. NET Power, Exelon, McDermott, Oxy Low Carbon Ventures, and 8 Rivers are developing the plant using this new cycle, and are building the demonstration power plant. Toshiba is in charge of development of important high pressure combustor and turbine in this system. This project is advanced through the following three steps.

- Development of the Oxy-fuel combustion technology in supercritical CO₂.
- Operation of the 50MWth demonstration plant for the confirmation of performance, operability, and reliability of this cycle.
- Construction of a commercial plant, utilizing the knowledge of 50MWth demonstration plant.

Toshiba carried out the full pressure (30MPa) burning test of 10MWth burner of 1/5 scale [10][11], and manufactured the combustor and turbine for 50MWth demonstration plant.

Since the combustion test of the combustor of a real scale was carried out at the demonstration plant before operating plant, we report about these results.

2. OVERVIEW OF SUPERCRITICAL CO₂ POWER GENERATION SYSTEM

The outline of this supercritical CO₂ power generation system is explained using Figure 1. In this system, natural gas, coal gasification gas, etc. can be used as fuel, and these fuel gases are burned with the oxygen separated from air with air separation unit. Fuel and oxygen burn in the condition of stoichiometric

ISBN978-4-89111-010-9

Copyright © 2019 Gas Turbine Society of Japan

fundamentally, rotate a turbine with high pressure and high temperature combustion gas of carbon dioxide (CO₂) and steam (H₂O) from a combustor, and a turbine drive a generator. The combustion gas which came out of a turbine is cooled in a cooler inside of a cycle, a plant is operated while extracting CO₂ and H₂O generated from C (carbon) and H (hydrogen) which are contained in fuel. The method of extracting CO₂ only extracts CO₂ which circulates through the inside of a cycle. CO₂ can be extracted without adding energy. Toshiba has further design and examination about fundamental issue like material, basic structure, cooling method etc., to develop a combustor and a turbine. The gas turbine consists of seven stages of nozzles and blades, and one can of combustor. Since it becomes operation in 30MPa, the casing has adopted the double casing (double shell structure) which is experienced with a USC steam turbine. The gas turbine where it installed to the demonstration plant is shown Figure 2.

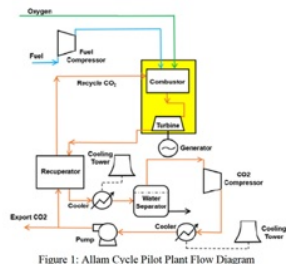


Figure 1: Allam Cycle Pilot Plant Flow Diagram



Figure 2: Installed Turbine at demonstration Plant

3. GAS TURBINE COMBUSTOR FOR SUPERCRITICAL CO₂ POWER GENERATION

In conventional gas turbine combustor which is widely used for power plant, the maximum working pressure is about 2 MPa, however, the maximum operation pressure of the gas turbine combustor in this supercritical CO₂ cycle power generation system has been 30MPa. Thus the main development subjects to a high pressure combustor is as follows.

- 1) Validate blow out point in CO₂ atmosphere include

after passing a recuperator, and water (H₂O) is separated. After the remaining CO₂ is pressurized with a compressor and a pump, it is made to hot condition by a recuperator, and is again supplied to a combustor. Although a great portion of CO₂ circulates through the supercritical condition and combustion characteristic like unburned fuel etc..

- 2) Validate cooling characteristic for combustor wall metal temperature.
- 3) Validate combustion dynamics.

Since the combustion phenomenon in supercritical CO₂ atmosphere has many unknown points at 30MPa, on actual pressure conditions, the combustion test of output 1/5 scale model was carried out on actual pressure condition, and it has so far checked about the development subject. In addition, the combustion test was carried out using the actual scale combustor as a performance check before installing in an actual turbine.

3.1 Actual Scale Combustion Test

Since big amount of CO₂ is needed, the actual scale combustion test is carried out using facility of demonstration plant in U.S. Texas. The cycle is shown in Figure 3. Combustion test rig is installed next to the turbine, the fuel for a combustion test has branched from the supply line to a turbine, and it is in the state where the gas turbine portion of the demonstration plant replaced combustion test rig, during the combustion test. Therefore, the exhaust gas from combustion test rig was sent to the actual recuperator and returns to combustor test rig, thus combustion tests are carried out by closed cycle operating condition like an actual plant.

In a power plant, combustion gas works in a turbine and then temperature and pressure decline.

However, at combustion tests, since there is no turbine, the temperature is decreased by CO₂ dilution and the pressure is reduced by a simulated nozzle and a pressure control valve. Therefore, from restriction of a plant facility, maximum pressure is 10MPa and maximum temperature at the combustor outlet is also lower than full load rating, and it becomes a maximum of 55% of full load rating with a heat output. Under this restriction, grasp of the combustion characteristics and confirmation of operability from ignition to a supercritical condition can be carried out.

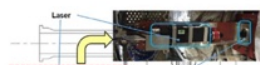


Figure 3: Flow Diagram of Full Scale Combustor Test

Sectional drawing of a combustion test rig is shown in Figure 4. The combustor consisting of a liner and a transition piece is the same size and form as what is installed in 50MWth turbine.

Combustion gas flows through the inside of the combustor of Figure 4 in the direction of a red arrow head, changes 90 degrees of flow directions in a transition piece, and flows toward the transition piece exit, i.e., a combustor outlet. The measurement section of thermometry and gas sampling, and the orifice which simulated first nozzle are set up at the combustor exit. The dilution section and pressure control valve for reducing temperature and pressure of combustion gas are installed at downstream of the measurement section. Combustion gas flows into the recuperator, after adjusting temperature and pressure. Moreover, the camera which can observe the inside of a combustor is installed in the portion of the blue arrow head of a transition piece part. The test rig appearance installed in the demonstration plant is shown in Figure 5.

within a combustor, the gas of the portion will ionize and it will be in a plasma state. The fuel oxygen mixture is lit using this condensed energy. The schematic diagram of a laser ignition device is shown in Fig. 6. Since a laser transmitter installs out of the casing of an atmospheric pressure, it is not receive the influence of pressure, and irradiates with a laser beam in a combustor through the window used as a pressure bulkhead. The laser ignition system is verified in this combustion test, and it is confirmed that it is satisfactory of specification.



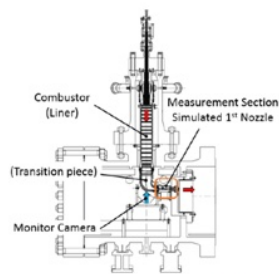


Figure 4: Cross section of Combustion Test Rig



Figure 5: Appearance of Combustion Test Rig

3.2 Ignition

In the conventional gas turbine combustor, the ignition plug of high tension is used for flame ignition. Although an ignition plug works at the time of ignition, after ignition, ignition plug is standing by in the position which can bear high temperature flame. However, an ignition plug continues receiving the high pressure of a combustor. This combustor may be set to 30MPa on rated load conditions as mentioned previously, and an ignition plug may not bear this pressure. Therefore, the ignition method by laser is adopted. If one point is made to condense a high energy laser beam

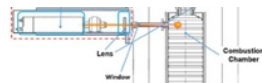


Figure 6: Laser Ignition System

3.3 Results of Combustion Tests

In this combustion tests, in addition to the operating condition of a gas turbine, it is also examined on the conditions which are separated from an operating condition about an equivalence ratio, supply oxygen concentration, the flow velocity, etc. Each flow rate data acquired at every 5 seconds, each pressure and thermal data acquired at every 2 seconds. Fig.7 shows the combustion exit temperature (left axis), and combustor inner pressure (right axis) versus time. Although automatic and manual control are possible for each flow of fuel, oxygen, and carbon dioxide, it mainly set up by manual control. Since it becomes automatic control when operating a turbine, quick load up is possible. Immediately after ignition, although combustor outlet temperature rises to 850°C, it is controlled toward a setting pressure and temperature, raising a burner internal pressure. Then, data is acquired, changing test conditions and after flame blow off, each flow conditions are set toward an ignition condition again.

Figure 8 shows the CO concentration at combustor exit versus combustor exit calculated temperature. These data is using what averaged the data acquired 5 minutes or more, after reaching a measurement condition. The equilibrium temperature calculated from the fuel, oxygen, and the carbon dioxide flow rate which are supplied to the combustor is used as the combustor exit temperature. Combustor exit temperature is at conditions 600degC or less, CO concentration at combustor exit is 300ppmvd or more. In the other temperature region, CO is less than 200ppmvd.

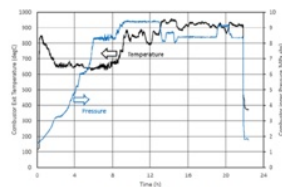


Figure 7: An Example of Trend Graph of Combustor Exit Temperature & Combustor Inner Pressure

Figure 9 shows combustion efficiency versus combustor exit calculated temperature. The combustion efficiency is calculated from the formula (1) using the concentration of CO and CH₄ at combustor exit. In addition, although the graphic display is not carried out, unburned CH₄ is 25ppmvd or less at any conditions. It is found that the combustion efficiency is below 99% at temperatures below 600degC, but approaches 100% at temperatures above 800degC, resulting in combustion efficiency equivalent to that of a conventional gas turbine combustor.

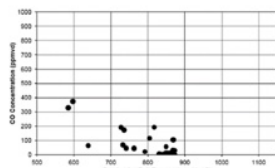


Figure 8: CO Concentration at Combustor Exit

$$\eta_{\text{comb}} = \left(1 - \frac{Q_{\text{CO}} + Q_{\text{CH}_4}}{Q_{\text{fuel}}}\right) \times 100 \quad (1)$$

(Q_{CO} , Q_{CH_4} : Calorific value of CO, CH₄ at the combustor exit, Q_{fuel} : Heat input to the combustor)

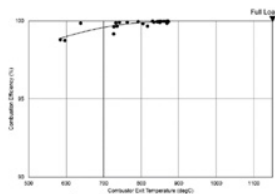


Figure 9: Combustion Efficiency

As Fig. 4 explained, the combustor consists of a liner and a transition piece, both are using the heat-resistant alloy, and the liner side adopts a slot film-cooling method, the transition piece side has adopted the whole surface film-cooling method, and it is using CO₂ as a coolant. The temperature of the metal outer surface of liner and the transition piece is measured by the thermocouples. The measured results show in Figure 10. The horizontal axis indicates position of measurement points, the vertical axis indicates measured temperature. In this combustion test, maximum heat load is 55%, and minimum load condition is 9%. As the heat load increases, the metal temperature increases, but it has been confirmed that the temperature is sufficiently low even at the maximum load of the combustion test. Also, the measured temperature is close to the design prediction value, and it can be predicted that the temperature will be sufficiently within the allowable temperature even under rated conditions.

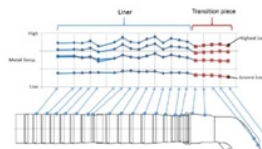


Figure 10: Distribution of Combustor Metal Temperature

4. CONCLUSION

Toshiba developed the turbine and combustor for the Allam Cycle supercritical CO₂ power generation system developed by NET Power, and carried out full scale combustion test with the actual combustor. The combustion tests are done from ignition to the maximum heat load of the test facility, and combustion characteristic and reliability are validated. The stable ignition performance is obtained by using the laser ignition system. The amount of CO at the exit of the combustor and the combustion efficiency are also validated as equivalent to those of the conventional gas turbine combustor.

The metal of the combustor is cooled enough in the combustion test range and close to the predicted temperature. This concludes that the prediction by heat transfer calculation in supercritical CO₂ is certain and the temperature in rated condition will fall within the allowable temperature.

This combustor is installed on the demonstration turbine and validation of the demonstration plant is conducted.

ACKNOWLEDGMENTS

We would like to thank NET Power, Exelon, McDermott, Oxy Low Carbon Ventures and 8 Rivers for their support to the combustion test.

REFERENCES

- [1] Y. Kobayashi, T. Kabata, K. Tomida, Y. Ando, M. Nishijima, N. Mataka, "Extremely High-efficiency Thermal Power System-Solid Oxide Fuel Cell (SOFC) Triple Combined-cycle System", Mitsubishi Heavy Industries Technical Review Vol. 48 No.3 (September 2011), pp.9-15.
- [2] Timothy J. Held, "INITIAL TEST RESULTS OF A MEGAWATT-CLASS SUPERCRITICAL CO₂ HEAT ENGINE", The 4th International Symposium - Supercritical CO₂ Power Cycles, September 9-10, 2014, Pittsburgh, Pennsylvania
- [3] S. Wright, R. Radd, M. Vernon, G. Rochau, P. Pickard, "operation and Analysis of a Supercritical CO₂ Brayton Cycle", SANDIA REPORT, SAND2010-0171
- [4] R.J. Allam, M. R. Palmer, G. W. Brown Jr., J. Fetvedt, D. Freed, H. Nomoto, M. Itoh, N. Okita, C. Jones Jr., "High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide", GHGT-11, 2012
- [5] R.J. Allam, J. Fetvedt, B. Forrest, C. Jones, H. Nomoto, M. Itoh, "A Novel, High-Efficiency, Oxy-Fuel Power Plant with Low-Cost Electricity Production and 100% Capture of Carbon Dioxide", POWER-GEN International 2013, 2013
- [6] R.J. Allam, J. Fetvedt, B. Forrest, D. Freed, "THE OXY-FUEL, SUPERCRITICAL CO₂ ALLAM CYCLE-NEW CYCLE DEVELOPMENTS TO PRODUCE EVEN LOWER-COST

ELECTRICITY FROM FOSSIL FUELS WITHOUT ATMOSPHERIC EMISSIONS", ASME Turbo Expo 2014, GT2014-26952

[7] Allam, R.J., Miles, R. P., and et al., "Demonstration of the Allam Cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture", 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, (2016)

[8] S. Martin, B. Forrest, N. Rafati, X. Lu, J. Fetvedt, M. McGroddy, B. Brown, R. Allam, D. Beauchamp, D. Freed, "Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility", 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, (2018)

[9] H. Nomoto, M. Itoh, B. Brown, J. Fetvedt, "Cycle and Turbine Development for the Supercritical Carbon Dioxide Allam Cycle", ICOPE-15-1176, (2015)

[10] Y. Iwai, M. Itoh, Y. Morisawa, S. Suzuki, D. Cusano, M. Harris, "Development Approach to the Combustor of Gas Turbine for Oxy-fuel, Supercritical CO₂ Cycle," ASME GT2015-43160, (2015)

[11] Y. Nakamura, Y. Iwai, M. Itoh, Y. Morisawa, T. Sasaki, D. Cusano, M. Harris, E. Petersen, "Development of Combustor for Supercritical CO₂ Turbine", IGTC2015,(2015)

Citations (0)

References (10)

Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility

Conference Paper

Full-text available

Oct 2018

 Scott Martin ·  Brock Alan Forrest ·  Navid Rafati ·  David Freed

[View](#) [Show abstract](#)

High Efficiency and Low Cost of Electricity Generation from Fossil Fuels While Eliminating Atmospheric Emissions, Including Carbon Dioxide

Article

Full-text available

Nov 2012

 Rodney John Allam ·  Miles R Palmer ·  Bill Brown ·  Charles Jones Jr

[View](#) [Show abstract](#)

ICOPE-15-1176 Cycle and Turbine Development for the Supercritical Carbon Dioxide Allam Cycle

Article

Nov 2015

 Hideo Nomoto ·  Masao Itoh ·  Bill Brown ·  Iwataro Sato

[View](#) [Show abstract](#)

Development Approach to the Combustor of Gas Turbine for Oxy-Fuel, Supercritical

CO2 Cycle

Conference Paper Jun 2015

Yasunori Iwai · Masao Itoh · Yuichi Morisawa · Mark Harris

[View](#) [Show abstract](#)

Extremely high efficiency power system -SOFC triple combined cycle system

Article Jan 2011

Y. Kobayashi · Y. Ando ·  Tatsuo Kabata · Norihisa Mataka

[View](#)

Extremely High-efficiency Thermal Power SystemSolid Oxide Fuel Cell (SOFC) Triple Combiend-cycle System

Sep 2011 · 9-15

Y Kobayashi · T Kabata · K Tomida · Y Ando · M Nishiura · N Mataka

Y. Kobayashi, T. Kabata, K. Tomida, Y. Ando, M. Nishiura, N. Mataka, "Extremely High-efficiency Thermal Power SystemSolid Oxide Fuel Cell (SOFC) Triple Combiend-cycle System", Mitsubishi Heavy Industries Technical Review Vol. 48 No.3 (September 2011), pp.9-15.

A Novel, High-Efficiency, Oxy-Fuel Power Plant with Low-Cost Electricity Production and 100% Capture of Carbon Dioxide

Jan 2013

R J Allam · J Fetvedt · B Forrest · C Jones · H Nomoto · M Itoh

R.J. Allam, J. Fetvedt, B. Forrest, C. Jones, H. Nomoto, M. Itoh, "A Novel, High-Efficiency, Oxy-Fuel Power Plant with Low-Cost Electricity Production and 100% Capture of Carbon Dioxide", POWER-GEN International 2013, 2013

Demonstration of the Allam Cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture

Jan 2016

R J Allam · R P Miles

Allam, R.J., Miles, R. P., and et al., "Demonstration of the Allam Cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture", 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, (2016)

Development of Combustor for Supercritical CO2 Turbine

Jan 2015

M Cusano · E Harris · Petersen

Cusano, M. Harris, E. Petersen, "Development of Combustor for Supercritical CO2 Turbine", IGTC2015, (2015)

Development of Combustor for Supercritical CO2 Turbine

Jan 2015

Y Nakamura · Y Iwai · M Itoh · Y Morisawa · T Sasaki · D Cusano · M Harris · E Petersen

Y. Nakamura, Y. Iwai, M. Itoh, Y. Morisawa, T. Sasaki, D. Cusano, M. Harris, E. Petersen, "Development of Combustor for Supercritical CO2 Turbine", IGTC2015,(2015)

Recommended publications

[Discover more](#)

Article Full-text available

Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercrit...

Article Full-text available

Comprehensive Thermodynamic Evaluation of the Natural Gas-Fired Allam Cycle at Full Load

July 2017 · Energy Procedia

 Rodney John Allam ·  Scott Martin · 
Brock Alan Forrest · [...] ·  James Manning

The Allam cycle is a novel CO₂, oxy-fuel power cycle that utilizes hydrocarbon fuels while inherently capturing approximately 100% of atmospheric emissions, including nearly all CO₂ emissions at a cost of electricity that is highly competitive with the best available energy production systems that do not employ CO₂ capture. The proprietary system achieves these results through a semi-closed-loop, ... [\[Show full abstract\]](#)

[View full-text](#)

March 2023 · Energies

Lorenzo Colleoni · Alessio Sindoni ·  Silvia Ravelli

In this study, thermodynamic modeling and simulations were used to optimize the design point performance of the Allam cycle. The topic fits perfectly with the strategies for power sector decarbonization toward net zero emission. In fact, it offers an environmentally friendlier alternative to natural gas combined cycle (NGCC) plants. The focus is on oxyfuel combustion that, combined with ... [\[Show full abstract\]](#)

[View full-text](#)

Article Full-text available

The flow path characteristics analysis for supercritical carbon dioxide gas turbines

January 2019 · E3S Web of Conferences

A. N. Rogalev · N. D. Rogalev ·  Vladimir Kindra · [...] · B A Makhmutov

Rising carbon dioxide concentration in the atmosphere is probably the main reason of global warming. The development of the oxy-fuel combustion cycles is a possible way to decrease the energy sector contribution in the emission process. However, an unusual composition and thermodynamic parameters of the working fluid cause the necessity of revision of the main equipment characteristics, ... [\[Show full abstract\]](#)

[View full-text](#)

Article Full-text available

Comparative analysis of the Allam cycle and the cycle of compressorless combined cycle gas turbine u...

January 2020 · E3S Web of Conferences

 Mikhail V. Sinkevich ·  Anatoly Kosoy ·  O. S. Popel

Nowadays, alternative thermodynamic cycles are actively studied. They allow to remove CO₂, formed as a result of fuel combustion, from a cycle without significant energy costs. Calculations have shown that such cycles may meet or exceed the most advanced power plants in terms of heat efficiency. The Allam cycle is recognized as one of the best alternative cycles for the production of electricity. ... [\[Show full abstract\]](#)

[View full-text](#)



Company

[About us](#)

[News](#)

[Careers](#)

Support

[Help Center](#)

Business solutions

[Advertising](#)

[Recruiting](#)

© 2008-2024 ResearchGate GmbH. All rights reserved.

[Terms](#) · [Privacy](#) · [Copyright](#) · [Imprint](#) · [Consent preferences](#)

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/338431114>

Supercritical CO₂ Demonstration Power Plant on Allam Cycle

Conference Paper · November 2019

CITATIONS

0

READS

2,224

1 author:



[Parikshit Jain](#)

University of California, Berkeley

5 PUBLICATIONS 8 CITATIONS

[SEE PROFILE](#)

High Pressure Combustion Test of Gas Turbine Combustor for 50MWth Supercritical CO₂ Demonstration Power Plant on Allam Cycle

Shinju Suzuki, Yasunori Iwai, Masao Itoh, Yuichi Morisawa, Parikshit Jain and Yoshihisa Kobayashi

Toshiba Energy Systems & Solutions Corporation, Keihin Product Operations
2-4, Suehiro-cho, Tsurumi-ku, Yokohama, 230-0045, Japan

ABSTRACT

Toshiba Energy Systems & Solutions Corporation is developing a combustor and turbine for a novel power generation system that can capture CO₂ while generating power at high efficiency while using supercritical CO₂ (sCO₂) as working fluid. The combustor is designed to generate 1150degC and 30MPa at turbine inlet condition for a 50MWth demonstration plant. Direct combustion system generates sCO₂ combustion gas by high pressure oxy-fuel combustion method. To confirm combustion performance under sCO₂ environment and in order to validate the design, testing has been done at various conditions of inlet parameters. The experimental maximum conditions were about 90 bar and 900 degC at combustor exit conditions, and this is equivalent to the middle load condition of the turbine. This combustion test campaign covered from initial ignition to tested maximum load condition with good operation and performance, and we confirmed a successful combustion performance under sCO₂ environment of Allam cycle.

1. INTRODUCTION

As one of the measure to prevent global warming, the reduction of CO₂ emissions through thermal power plant is necessary. Increasing CO₂ emissions from a thermal power plant has been a problem, the industrial shift from thermal power supply to renewable power supply is expanding. However, to keep stable grid control, the renewable power supply may require a backup by thermal power generation, in which new construction opportunities are limited. Hence thermal power supply is counterpart of renewable power supply and the research and development for reducing CO₂ emissions have been continued as well.

One of the direction is increasing thermal efficiency, such as the combined cycle of gas turbine and steam turbine configuration, which results in a reduce fuel use, and can reduce CO₂ emissions. Furthermore, development of a more advanced cycle of unifying SOFC (solid-oxide fuel cell) and combined cycle power generation is carried out, and this is called the "triple combined cycle" which may improve thermal efficiency greatly [1]. CCS (carbon recovery and storage) is separating CO₂ in a combustion exhaust gas with a chemical method, and is one of the technology which reduces the CO₂ emissions from a thermal power plant. However, the energy for carrying out scavenging of CO₂ is required, therefore the thermal efficiency of a plant goes down. In order to transport CO₂ collected by this system and to use for commercial benefit, application of pressure is needed. This pressurization process requires large energy. Application of the supercritical CO₂ closed-cycle technology to a thermal power plant is one of the most

effective method of generating power, without discharging CO₂ outside. Echogen electric power system develops the supercritical CO₂ cycle which adopted the heater and the non-combustion system [2] and Sandia National Laboratories are advancing research on an efficient Brayton cycle by the supercritical CO₂ cycle using solar heat, a nuclear heat source, and a fossil fuel heat source [3].

Supercritical CO₂ turbine system (Allam Cycle) proposed by NET Power can collect CO₂ with high purity, without losing the energy by compression, and can attain high thermal efficiency (equivalent to the existing combined cycle plant) [4][5][6][7][8][9]. In this cycle, natural gas and oxygen reacts to CO₂ and H₂O in a combustor. The exhaust gas then drives a turbine with the mixed gas of CO₂ and H₂O which are combustion gas. After the combustion gas that carried out turbine driving passes a recuperator, H₂O is separated, and it is compressed with a compressor, and part of CO₂ is separated and collected. After the temperature increase of the remaining combustion gas is carried out by a recuperator, it is again supplied to a combustor. This cycle enables realization of an ideal near-zero-emission power-plant system. NET Power, Exelon, McDermott, Oxy Low Carbon Ventures, and 8 Rivers are developing the plant using this new cycle, and are building the demonstration power plant. Toshiba is in charge of development of important high pressure combustor and turbine in this system. This project is advanced through the following three steps.

- Development of the Oxy-fuel combustion technology in supercritical CO₂.
- Operation of the 50MWth demonstration plant for the confirmation of performance, operability, and reliability of this cycle.
- Construction of a commercial plant, utilizing the knowledge of 50MWth demonstration plant.

Toshiba carried out the full pressure (30MPa) burning test of 10MWth burner of 1/5 scale [10][11], and manufactured the combustor and turbine for 50MWth demonstration plant.

Since the combustion test of the combustor of a real scale was carried out at the demonstration plant before operating plant, we report about these results.

2. OVERVIEW of SUPERCRITICAL CO₂ POWER GENERATION SYSTEM

The outline of this supercritical CO₂ power generation system is explained using Figure 1. In this system, natural gas, coal gasification gas, etc. can be used as fuel, and these fuel gases are burned with the oxygen separated from air with air separation unit. Fuel and oxygen burn in the condition of stoichiometric

fundamentally, rotate a turbine with high pressure and high temperature combustion gas of carbon dioxide (CO_2) and steam (H_2O) from a combustor, and a turbine drive a generator. The combustion gas which came out of a turbine is cooled in a cooler inside of a cycle, a plant is operated while extracting CO_2 and H_2O generated from C (carbon) and H (hydrogen) which are contained in fuel. The method of extracting CO_2 only extracts CO_2 which circulates through the inside of a cycle. CO_2 can be extracted without adding energy. Toshiba has furthered design and examination about fundamental issue like material, basic structure, cooling method etc., to develop a combustor and a turbine. The gas turbine consists of seven stages of nozzles and blades, and one can of combustor. Since it becomes operation in 30MPa, the casing has adopted the double casing (double shell structure) which is experienced with a USC steam turbine. The gas turbine where it installed to the demonstration plant is shown Figure 2.

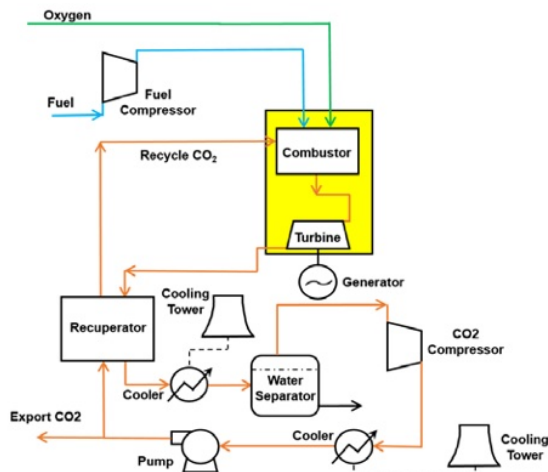


Figure 1: Allam Cycle Pilot Plant Flow Diagram



Figure 2: Installed Turbine at demonstration Plant

3. GAS TURBINE COMBUSTOR for SUPERCRITICAL CO_2 POWER GENERATION

In conventional gas turbine combustor which is widely used for power plant, the maximum working pressure is about 2 MPa, however, the maximum operation pressure of the gas turbine combustor in this supercritical CO_2 cycle power generation system has been 30MPa. Thus the main development subjects to a high pressure combustor is as follows.

- 1) Validate blow out point in CO_2 atmosphere include

after passing a recuperator, and water (H_2O) is separated. After the remaining CO_2 is pressurized with a compressor and a pump, it is made to hot condition by a recuperator, and is again supplied to a combustor. Although a great portion of CO_2 circulates through the supercritical condition and combustion characteristic like unburned fuel etc...

- 2) Validate cooling characteristic for combustor wall metal temperature.

- 3) Validate combustion dynamics.

Since the combustion phenomenon in supercritical CO_2 atmosphere has many unknown points at 30MPa, on actual pressure conditions, the combustion test of output 1 / 5 scale model was carried out on actual pressure condition, and it has so far checked about the development subject. In addition, the combustion test was carried out using the actual scale combustor as a performance check before installing in an actual turbine.

3.1 Actual Scale Combustion Test

Since big amount of CO_2 is needed, the actual scale combustion test is carried out using facility of demonstration plant in U.S. Texas. The cycle is shown in Figure 3. Combustion test Rig is installed next to the turbine, the fuel for a combustion test has branched from the supply line to a turbine, and it is in the state where the gas turbine portion of the demonstration plant replaced combustion test rig, during the combustion test. Therefore, the exhaust gas from combustion test rig was sent to the actual recuperator and return to combustion test rig, thus combustion tests are carried out by closed cycle operating condition like an actual plant.

In a power plant, combustion gas works in a turbine and then temperature and pressure decline.

However, at combustion tests, since there is no turbine, the temperature is decreased by CO_2 dilution and the pressure is reduced by a simulated nozzle and a pressure control valve. Therefore, from restriction of a plant facility, maximum pressure is 10MPa and maximum temperature at the combustor outlet is also lower than full load rating, and it becomes a maximum of 55% of full load rating with a heat output. Under this restriction, grasp of the combustion characteristics and confirmation of operability from ignition to a supercritical condition can be carried out.

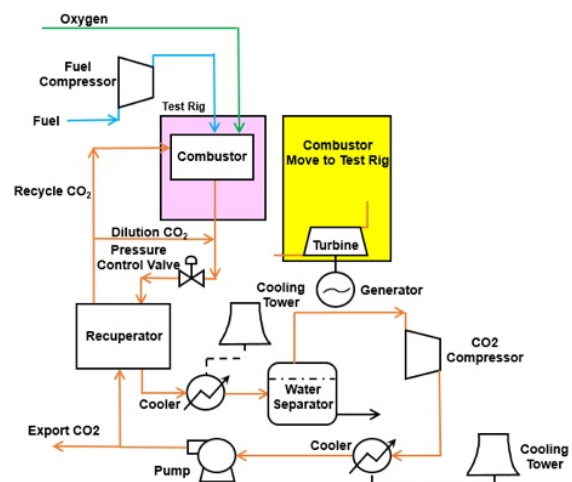


Figure 3: Flow Diagram of Full Scale Combustor Test

Sectional drawing of a combustion test rig is shown in Figure 4. The combustor consisting of a liner and a transition piece is the same size and form as what is installed in 50MWth turbine.

Combustion gas flows through the inside of the combustor of Figure 4 in the direction of a red arrow head, changes 90 degrees of flow directions in a transition piece, and flows toward the transition piece exit, i.e., a combustor outlet. The measurement section of thermometry and gas sampling, and the orifice which simulated first nozzle are set up at the combustor exit. The dilution section and pressure control valve for reducing temperature and pressure of combustion gas are installed at downstream of the measurement section. Combustion gas flows into the recuperator, after adjusting temperature and pressure. Moreover, the camera which can observe the inside of a combustor is installed in the portion of the blue arrow head of a transition piece part. The test rig appearance installed in the demonstration plant is shown in Figure 5.

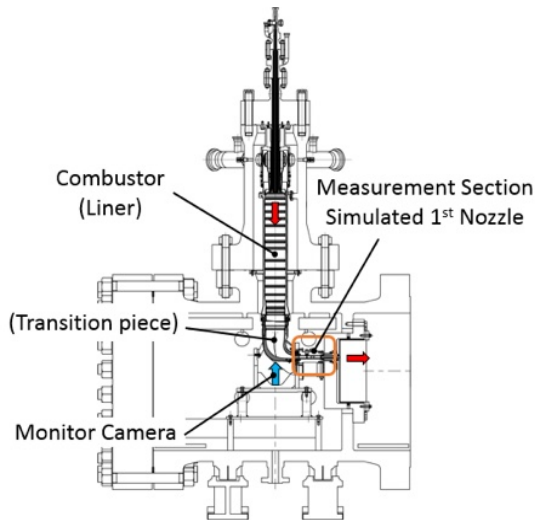


Figure 4: Cross section of Combustion Test Rig



Figure 5: Appearance of Combustion Test Rig

3.2 Ignition

In the conventional gas turbine combustor, the ignition plug of high tension is used for flame ignition. Although an ignition plug works at the time of ignition, after ignition, ignition plug is standing by in the position which can bear high temperature flame. However, an ignition plug continues receiving the high pressure of a combustor. This combustor may be set to 30MPa on rated load conditions as mentioned previously, and an ignition plug may not bear this pressure. Therefore, the ignition method by laser is adopted. If one point is made to condense a high energy laser beam

within a combustor, the gas of the portion will ionize and it will be in a plasma state. The fuel oxygen mixture is lit using this condensed energy. The schematic diagram of a laser ignition device is shown in Fig. 6. Since a laser transmitter installs out of the casing of an atmospheric pressure, it is not receive the influence of pressure, and irradiates with a laser beam in a combustor through the window used as a pressure bulkhead. The laser ignition system is verified in this combustion test, and it is confirmed that it is satisfactory of specification.

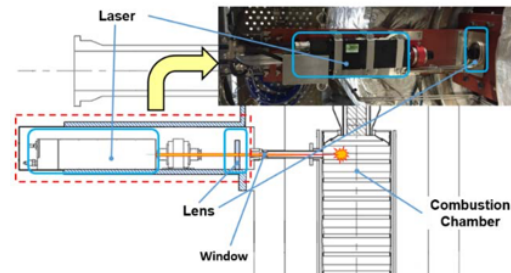


Figure 6: Laser Ignition System

3.3 Results of Combustion Tests

In this combustion tests, in addition to the operating condition of a gas turbine, it is also examined on the conditions which are separated from an operating condition about an equivalence ratio, supply oxygen concentration, the flow velocity, etc. Each flow rate data acquired at every 5 seconds, each pressure and thermal data acquired at every 2 seconds. Fig.7 shows the combustor exit temperature (left axis), and combustor inner pressure (right axis) versus time. Although automatic and manual control are possible for each flow of fuel, oxygen, and carbon dioxide, it mainly set up by manual control. Since it becomes automatic control when operating a turbine, quick load up is possible. Immediately after ignition, although combustor outlet temperature rises to 850°C, it is controlled toward a setting pressure and temperature, raising a burner internal pressure. Then, data is acquired, changing test conditions and after flame blow off, each flow conditions are set toward an ignition condition again.

Figure 8 shows the CO concentration at combustor exit versus combustor exit calculated temperature. These data is using what averaged the data acquired 5 minutes or more, after reaching a measurement condition. The equilibrium temperature calculated from the fuel, oxygen, and the carbon dioxide flow rate which are supplied to the combustor is used as the combustor exit temperature. Combustor exit temperature is at conditions 600degC or less, CO concentration at combustor exit is 300ppmvd or more. In the other temperature region, CO is less than 200ppmvd.

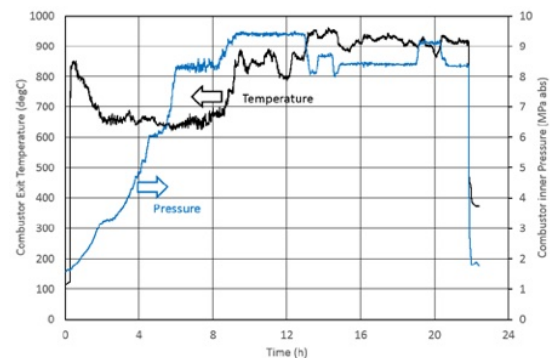


Figure 7: An Example of Trend Graph of Combustor Exit Temperature & Combustor Inner Pressure

Figure 9 shows combustion efficiency versus combustor exit calculated temperature. The combustion efficiency is calculated from the formula (1) using the concentration of CO and CH₄ at combustor exit. In addition, although the graphic display is not carried out, unburned CH₄ is 25ppmvd or less at any conditions. It is found that the combustion efficiency is below 99% at temperatures below 600degC, but approaches 100% at temperatures above 800degC, resulting in combustion efficiency equivalent to that of a conventional gas turbine combustor.

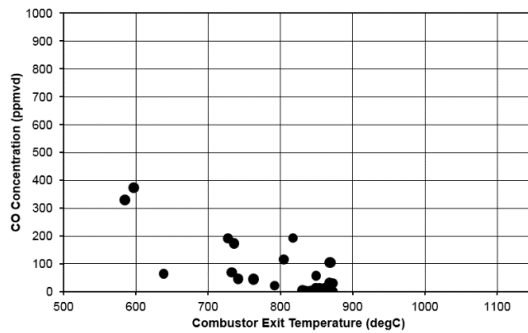


Figure 8: CO Concentration at Combustor Exit

$$\eta_{\text{comb}} = \left(1 - \frac{Q_{\text{co}} + Q_{\text{ch4}}}{Q_{\text{fuel}}}\right) * 100 \quad - (1)$$

(Q_{co}, Q_{ch4}: Calorific value of CO, CH₄ at the combustor exit,
Q_{fuel}: Heat input to the combustor)

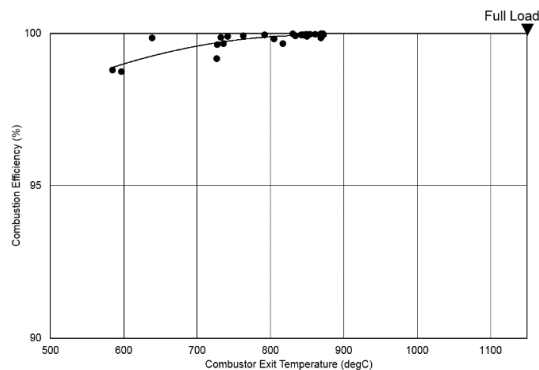


Figure 9: Combustion Efficiency

As Fig. 4 explained, the combustor consists of a liner and a transition piece, both are using the heat-resistant alloy, and the liner side adopts a slot film-cooling method, the transition piece side has adopted the whole surface film-cooling method, and it is using CO₂ as a coolant. The temperature of the metal outer surface of liner and the transition piece is measured by the thermocouples. The measured results show in Figure 10. The horizontal axis indicates position of measurement points, the vertical axis indicates measured temperature. In this combustion test, maximum heat load is 55%, and minimum load condition is 9%. As the heat load increases, the metal temperature increases, but it has been confirmed that the temperature is sufficiently low even at the maximum load of the combustion test. Also, the measured temperature is close to the design prediction value, and it can be predicted that the temperature will be sufficiently within the allowable temperature even under rated conditions.

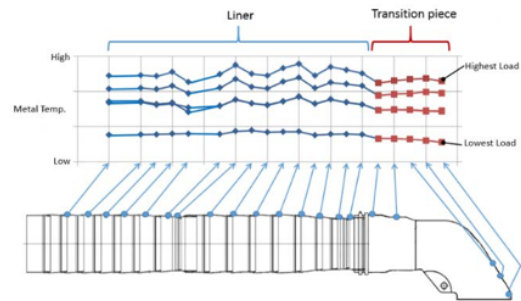


Figure 10: Distribution of Combustor Metal Temperature

4. CONCLUSION

Toshiba developed the turbine and combustor for the Allam Cycle supercritical CO₂ power generation system developed by NET Power, and carried out full scale combustion test with the actual combustor. The combustion tests are done from ignition to the maximum heat load of the test facility, and combustion characteristic and reliability are validated. The stable ignition performance is obtained by using the laser ignition system. The amount of CO at the exit of the combustor and the combustion efficiency are also validated as equivalent to those of the conventional gas turbine combustor.

The metal of the combustor is cooled enough in the combustion test range and close to the predicted temperature. This concludes that the prediction by heat transfer calculation in supercritical CO₂ is certain and the temperature in rated condition will fall within the allowable temperature.

This combustor is installed on the demonstration turbine and validation of the demonstration plant is conducted.

ACKNOWLEDGMENTS

We would like to thank NET Power, Exelon, McDermott, Oxy Low Carbon Ventures and 8 Rivers for their support to the combustion tests.

REFERENCES

- [1] Y. Kobayashi, T. Kabata, K. Tomida, Y. Ando, M. Nishiura, N. Mataka, "Extremely High-efficiency Thermal Power System-Solid Oxide Fuel Cell (SOFC) Triple Combien-cycle System", Mitsubishi Heavy Industries Technical Review Vol. 48 No.3 (September 2011), pp.9-15.
- [2] Timonhy J. Held, "INITIAL TEST RESULTS OF A MEGAWATT-CLASS SUPERCRITICAL CO₂ HEAT ENGINE", The 4th International Symposium – Supercritical CO₂ Power Cycles, September 9-10, 2014, Pittsburgh, Pennsylvania
- [3] S. Wright, R. Radel, M. Vernon, G. Rochau, P. Pickard, "operation and Analysis of a Supercritical Co₂ Brayton Cycle", SANDIA REPORT, SAND2010-0171
- [4] R.J. Allam, M. R. Palmer, G. W. Brown Jr., J. Fetvedt, D. Freed, H. Nomoto, M. Itoh, N. Okita, C. Jones Jr., "High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide", GHGT-11, 2012
- [5] R.J. Allam, J. Fetvedt, B. Forrest, C. Jones, H. Nomoto, M. Itoh, "A Novel, High-Efficiency, Oxy-Fuel Power Plant with Low-Cost Electricity Production and 100% Capture of Carbon Dioxide", POWER-GEN International 2013, 2013
- [6] R.J. Allam, J. Fetvedt, B. Forrest, D. Freed, "THE OXY-FUEL, SUPERCRITICAL CO₂ ALLAM CYCLE: NEW CYCLE DEVELOPMENTS TO PRODUCE EVEN LOWER-COST

ELECTRICITY FROM FOSSIL FUELS WITHOUT ATMOSPHERIC EMISSIONS”, ASME Turbo Expo 2014, GT2014-26952

[7] Allam, R.J., Miles, R. P., and et al., “Demonstration of the Allam Cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture“, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, (2016)

[8] S. Martin, B. Forrest, N. Rafati, X. Lu, J. Fetvedt, M. McGroddy, B. Brown, R. Allam, D. Beauchamp, D. Freed, “Progress Update on the Allam Cycle: Commercialization of NET Power and the NET Power Demonstration Facility”, 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, (2018)

[9] H. Nomoto, M. Itoh, B. Brown, J. Fetvedt, “Cycle and Turbine Development for the Supercritical Carbon Dioxide Allam Cycle”, ICOPE-15-1176, (2015)

[10] Y. Iwai, M. Itoh, Y. Morisawa, S. Suzuki, D. Cusano, M. Harris, “Development Approach to the Combustor of Gas Turbine for Oxy-fuel, Supercritical CO₂ Cycle,” ASME GT2015-43160, (2015)

[11] Y. Nakamura, Y. Iwai, M. Itoh, Y. Morisawa, T. Sasaki, D. Cusano, M. Harris, E. Petersen, “Development of Combustor for Supercritical CO₂ Turbine”, IGTC2015,(2015)

EXHIBIT MARTIN05

To Declaration of June Ann Munford

[Advanced Search](#)[All issues](#) ▶ [Volume 178 \(2020\)](#) ▶ [E3S Web Conf., 178 \(2020\) 01027](#) ▶ Abstract

- Browse
 - [All issues](#)
 - [Forthcoming](#)
 - [Series](#)
- About the journal
 - [Aims and scope](#)
 - [Editorial board](#)
 - [Indexed in](#)
 - [Publishing Policies & Ethics](#)
 - [Published by](#)
- [For conference organizers](#)
- [For authors](#)
- [News](#)
- All open access proceedings journals
 - [BIO Web of Conferences](#)
 - [ITM Web of Conferences](#)
 - [MATEC Web of Conferences](#)
 - [E3S Web of Conferences](#)
 - [SHS Web of Conferences](#)
 - [EPJ Web of Conferences](#)
- [Client feedback](#)
- [FAQ](#)
- [Contact](#)
- [Request a quote](#)

Open Access

Issue	E3S Web Conf. Volume 178, 2020 High Speed Turbomachines and Electrical Drives Conference 2020 (HSTED-2020)
Article Number	01027
Number of page(s)	7
DOI	https://doi.org/10.1051/e3sconf/202017801027
Published online	09 July 2020

E3S Web of Conferences 178, 01027 (2020)

Natural Gas-Oxygen Combustion in a Super-Critical Carbon Dioxide Gas Turbine Combustor

Ivan Komarov*, Daria Kharlamova, Bulat Makhmutov, Sofia Shabalova and Ilya Kaplanovich

National Research University "Moscow Power Engineering Institute", Moscow, Russia

* Corresponding author: komarov_vanya@bk.ru

Abstract

The paper presents results for chemical kinetics of combustion process in the combustor of oxy-fuel cycle super-critical carbon dioxide gas turbine based on the Allam thermodynamic cycle. The work shows deviation of the normal flame propagation velocity for the case of transition from the traditional natural gas combustion in the N₂ diluent environment to the combustion at super-high pressure up to 300 bar in CO₂ diluent. The chemical kinetics parametric study involved the Chemkin code with the GRI-Mesh 3.0 kinetic mechanism. This mechanism provides good correspondence between calculation results and test data. The CO₂ and N₂ diluents temperature, pressure and contents influence the flame propagation velocity and the chemical kinetics parameters in the two gas turbine types. It is demonstrated that the CO₂ diluent slows down chemical reactions stronger than the N₂ one. The flame propagation velocity in carbon dioxide is four time smaller than in the N₂

one. In the oxy-fuel cycle combustor a pressure increase reduces the flame propagation velocity. Increase of the CO₂ content from 60 to 79% reduces the flame propagation velocity for 65% at atmospheric pressure and for 94% at super-critical pressure. An increase of the combustor inlet mixture temperature from 300 to 1100 K at super-critical pressure causes the flame propagation velocity increase for 94%. The flame propagation velocities compatible with the traditional gas turbines may be reached at the CO₂ diluent content of the O₂ + CO₂ mixture in the active combustion zone must be below 50%.

© The Authors, published by EDP Sciences, 2020



This is an Open Access article distributed under the terms of the [Creative Commons Attribution License 4.0](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

[Homepage](#)

[Table of Contents](#)

[◀ Previous article](#) [Next article ▶](#)

ARTICLE CONTENTS

[- Abstract](#)
[- PDF \(712.4 KB\)](#)
[- References](#)

DATABASE LINKS

[NASA ADS Abstract Service](#)

METRICS

Show article metrics

SERVICES

Articles citing this article
[CrossRef \(7\)](#)

Same authors
[- Google Scholar](#)
[- EDP Sciences database](#)

[Recommend this article](#)
[Download citation](#)
[Alert me if this article is corrected](#)
[Alert me if this article is cited](#)

RELATED ARTICLES

[Effect of Syngas Moisture Content on the Emissions of Micro-Gas Turbine Fueled with Syngas/LPG in Dual Fuel Mode](#)
 MATEC Web of Conferences 13, 02012 (2014)

[Effects of N₂/CO₂ dilution on flame propagation velocities and quenching distances of oxy-methane premixed mixtures using an Annular-Stepwise-Diverging-Tube \(ASDT\)](#)
 Math. Model. Nat. Phenom. 13 (2018) 55

[Denitrogenation \(or Oxyfuel Concepts\)](#)
 Oil & Gas Science and Technology - Rev. IFP, Vol. 60 (2005), No.3, pp. 485-495

[More](#)

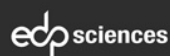
BOOKMARKING



[Reader's services](#)
[Email-alert](#)

E3S Web of Conferences

eISSN: 2267-1242



[Mentions légales](#) [Contacts](#) [Privacy policy](#)

A Vision4Press website

Natural Gas-Oxygen Combustion in a Super-Critical Carbon Dioxide Gas Turbine Combustor

Ivan Komarov^{1,*}, Daria Kharlamova¹, Bulat Makhmutov¹, Sofia Shabalova¹, and Ilya Kaplanovich¹

¹National Research University "Moscow Power Engineering Institute", Moscow, Russia

Abstract. The paper presents results for chemical kinetics of combustion process in the combustor of oxy-fuel cycle super-critical carbon dioxide gas turbine based on the Allam thermodynamic cycle. The work shows deviation of the normal flame propagation velocity for the case of transition from the traditional natural gas combustion in the N₂ diluent environment to the combustion at super-high pressure up to 300 bar in CO₂ diluent. The chemical kinetics parametric study involved the Chemkin code with the GRI-Mesh 3.0 kinetic mechanism. This mechanism provides good correspondence between calculation results and test data. The CO₂ and N₂ diluents temperature, pressure and contents influence the flame propagation velocity and the chemical kinetics parameters in the two gas turbine types. It is demonstrated that the CO₂ diluent slows down chemical reactions stronger than the N₂ one. The flame propagation velocity in carbon dioxide is four time smaller than in the N₂ one. In the oxy-fuel cycle combustor a pressure increase reduces the flame propagation velocity. Increase of the CO₂ content from 60 to 79% reduces the flame propagation velocity for 65% at atmospheric pressure and for 94% at super-critical pressure. An increase of the combustor inlet mixture temperature from 300 to 1100 K at super-critical pressure causes the flame propagation velocity increase for 94%. The flame propagation velocities compatible with the traditional gas turbines may be reached at the CO₂ diluent content of the O₂ + CO₂ mixture in the active combustion zone must be below 50%.

1 Introduction

Transition to the environmentally friendly, low toxic and greenhouse emissions cycles is one of the most prospective directions for the hydro-carbon power production industry. The closed gas turbine cycles on super-critical carbon dioxide with organic fuel combustion in pure oxygen seem very attractive. In these terms, the Allam cycle (Figure 1) promises maximal production efficiency and nearly zero emissions [1-5].

Introduction of the Allam cycle requires solutions of a range of research problems that includes development of the power equipment analysis to operate with new heat carriers at non-traditional thermodynamic parameters.

The Allam cycle parameters of oxy-fuel combustion differ from the traditional gas turbines by the following parameters:

- The oxy-fuel cycle combustor pressure of 300 bar instead of the traditional gas turbines values below 30 bar;
- Methane is burned in the carbon dioxide environment instead of the nitrogen diluent in traditional gas turbines.

The common combustor analysis is based on the detailed description of methane combustion in air

environment at pressures up to 30 bar. The analysis determines the complete fuel burnout conditions, oxygen-fuel mixture velocity at the combustor entry and the components residence time for the high temperature reaction zone. The oxy-fuel cycle combustor development involves methane oxygen combustion in the carbon dioxide environment at super-critical pressure up to 300 bar and investigation of the flow aerodynamic structure at the oxygen-fuel mixture formation and CH₄-O₂ combustion [6-9]. This paper discloses the chemical kinetics investigation that makes a base for further 3-D simulation of the CH₄-O₂-CO₂ combustion and the results that are adequate to the actual processes. Especially important is the transition from N₂ to CO₂ combined with the combustor inlet parameters increase that is related to the normal flame propagation velocity. This parameter depends upon temperature, pressure and the components contents but is not related to the combustor burner design, or the flame tube structures. The analysis results provide a conclusion on the necessity to change the combustor inlet oxygen-fuel mixture velocity and the diluent content ($\gamma = \text{CO}_2 / (\text{CO}_2 + \text{O}_2)$) that provide the flame stability and complete burn-out. The combustor envelope dimensions are similar to the traditional gas turbines [10-12].

* Corresponding author: komarov_vanya@bk.ru

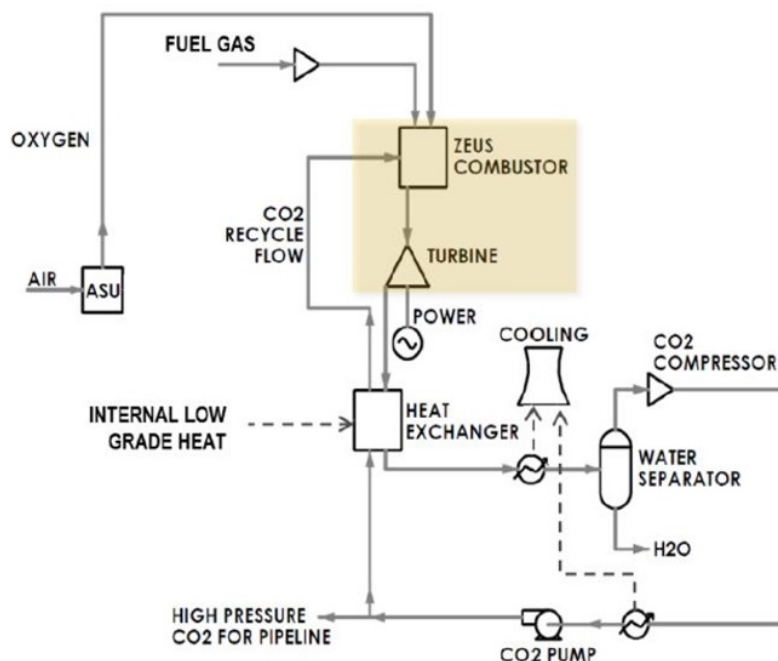


Fig. 1. Flow chart of Allam cycle on natural gas fuel.

2 Materials and Methods

The parametric study on influence of the diluent type and concentration upon the CH₄-O₂- CO₂ and CH₄-O₂-N₂ mixture combustion kinetic parameters was carried out with the Chemkin computer simulation code.

In the study were selected the following detailed kinetic mechanisms that allow calculations with numerous mixture contents and initial parameters. The following two kinetic mechanisms were considered [13-17]:

- Mechanism #1: GRI-Mesh 3.0 developed for the natural gas combustion including the chemical incomplete combustion. The mechanism basic kinetics

involves 53 intermediate reaction products and 325 convertible chemical reactions of the methane transformation into complete combustion products;

- Mechanism #2: USC II involves 325 components and 725 convertible reactions applied to a broad spectrum of combustion scripts. The USC II model was developed on the combustion mechanism GRI-Mesh 3.0, the hydrogen and carbon monoxide combustion, the fuel combustion model C3 and the complex model of ethylene and acetylene combustion. The both models include the reaction velocity data from the recent actual investigations.

The results were verified by comparison with the test data of the papers [18-20].

The results show that at atmospheric pressure the

Table 1. Summarizes input data for the chemical kinetics parametric studies on the N₂ and CO₂ diluents at different pressures, diluent contents and reactor inlet temperatures.

Analysis series	Pressure, bar	Diluent type and mass content, γ	Gas mixture temperature upstream combustion reactor, K	Oxidizer excess coefficient
Diluent CO ₂				
1	1	0.60	300	0.7-1.4
2	1	0.64	300	0.7-1.4
3	1	0.68	300	0.7-1.4
4	1	0.79	300	0.7-1.4
5	20-300	0.60	300	1.0
6	20-300	0.64	300	1.0
7	20-300	0.71	300	1.0
8	20-300	0.74	300	1.0
9	20-300	0.79	300-1200	1.0
Diluent N ₂				
10	1	0.79	300	0.7-1.4
11	20-300	0.79	300-1200	1.0

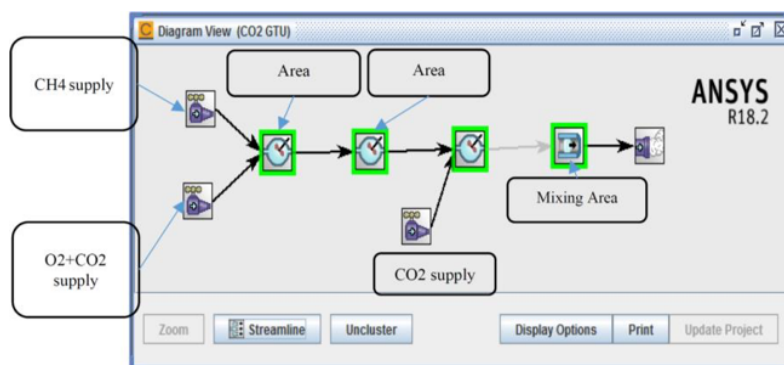


Fig. 2. Combustor structure comprised of the Chemkin reactors.

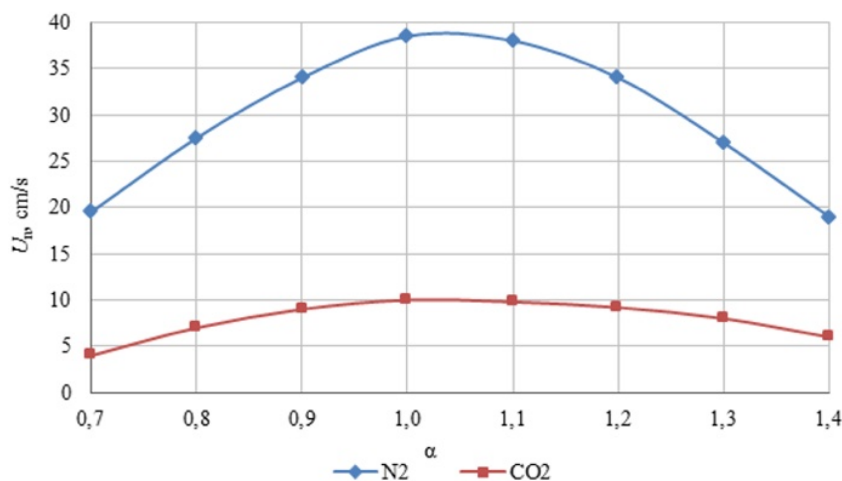


Fig. 3. Normal flame propagation velocity in the N2 and CO2 diluents ($\gamma = 0.79$) at atmospheric pressure and gas temperature 300 K.

both detailed mechanisms demonstrate moderate deviations from the test data. At high pressure the USC II shows overrated estimations of the flame propagation velocity and the GRI-Mesh 3.0 underrates it. The GRI-Mesh 3.0 calculation error is below 3.5% and the USC II One is above 6%. The further calculations were carried out with the GRI-Mesh 3.0.

Figure 2 shows the combustor structure model comprised of a set of elementary reactors. The model includes the staged supply of CO2 diluent into the combustor. The mixture is ignited at the CO2 volumetric content equal to the value γ . The second CO2 flow cools the combustor walls, the third flow supplied to the end of active combustion zone mixes with the main flow as to reach the target temperature.

3 Results

Figures 3-6 show the normal flame propagation velocities in the N2 and CO2 environments at different initial values of oxygen-fuel mixture temperature and

pressure, oxidizer excess and the diluent contents in diluent-oxygen mixture.

The calculation results show that the carbon dioxide is a stronger chemical reactions inhibitor than nitrogen. The maximal flame surface propagation velocity is 10 cm/s, and with the N2 diluent at other conditions being equal it is almost 40 cm/s. In average at the oxidizer excess coefficient from 0.7 to 1.4 the normal flame propagation velocity in the carbon dioxide environment is four times smaller.

Reduction of the CO2 content in its mixture with oxidizer at γ reduction for 0.1 increases the flame propagation velocity for 2 cm/s in average. The maximal increase occurs at the CO2 content reduction from 0.74 to 0.6. In the whole range of oxidizer excess coefficients the maximal flow propagation velocity occurs at $\alpha = 1$.

Pressure increase reduces the normal flame propagation velocity. The maximal reduction occurs at moderate pressure values below 70 bar. The further pressure increase also reduces U_n , but in a remarkably smaller degree.

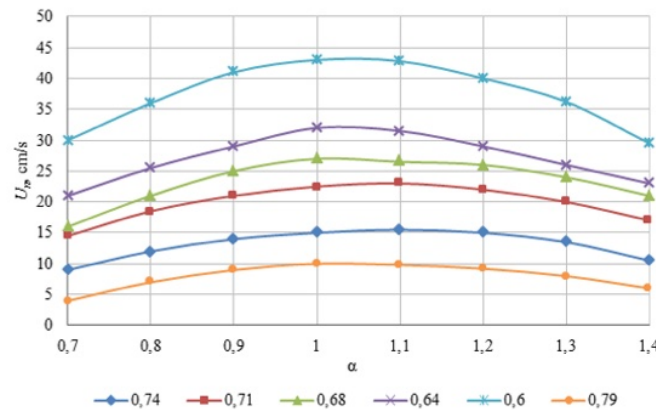


Fig. 4. Normal flame propagation velocity at different γ (CO₂) and oxidizer excess values at atmospheric pressure and gas temperature 300 K.

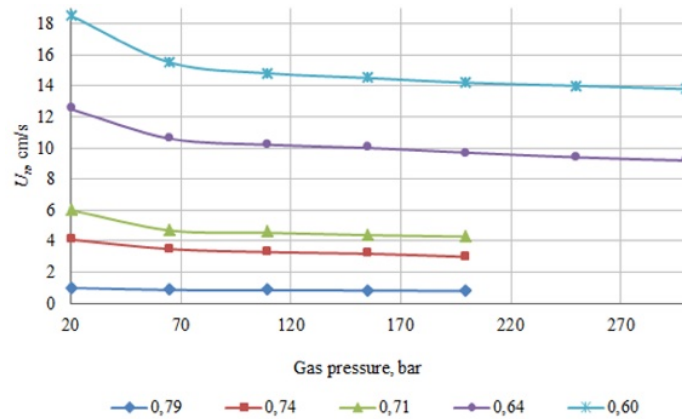


Fig. 5. Normal flame propagation velocity at different pressure and γ (CO₂) values at gas temperature 300 K.

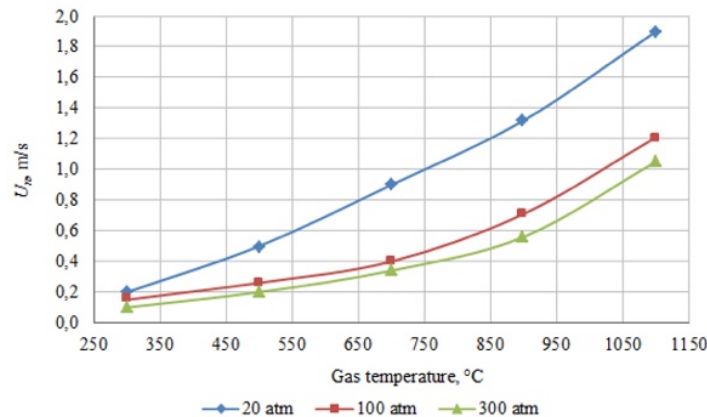


Fig. 6. Normal flame propagation velocity at in the CO₂ diluent at different combustor inlet gas pressure and temperature ($\gamma = 0.71$).

According to the **Ошибка! Источник ссылки не найден.** results increase of the gas mixture temperature is followed by the normal flame propagation velocity growth at all pressure values, and the growth rate is non-linear. The temperature increase from 900 to 1100°C increases the velocity for average 22 cm/s. At lower

mixture temperatures the similar 200°C temperature increase causes only a 8-10 cm/s increase. At the initial mixture temperature T_0 convection and radiation heat transfer heats the mixture up to the ignition temperature T_i that begins exothermal reactions and the mixture temperature grows. It is obvious that when the mixture

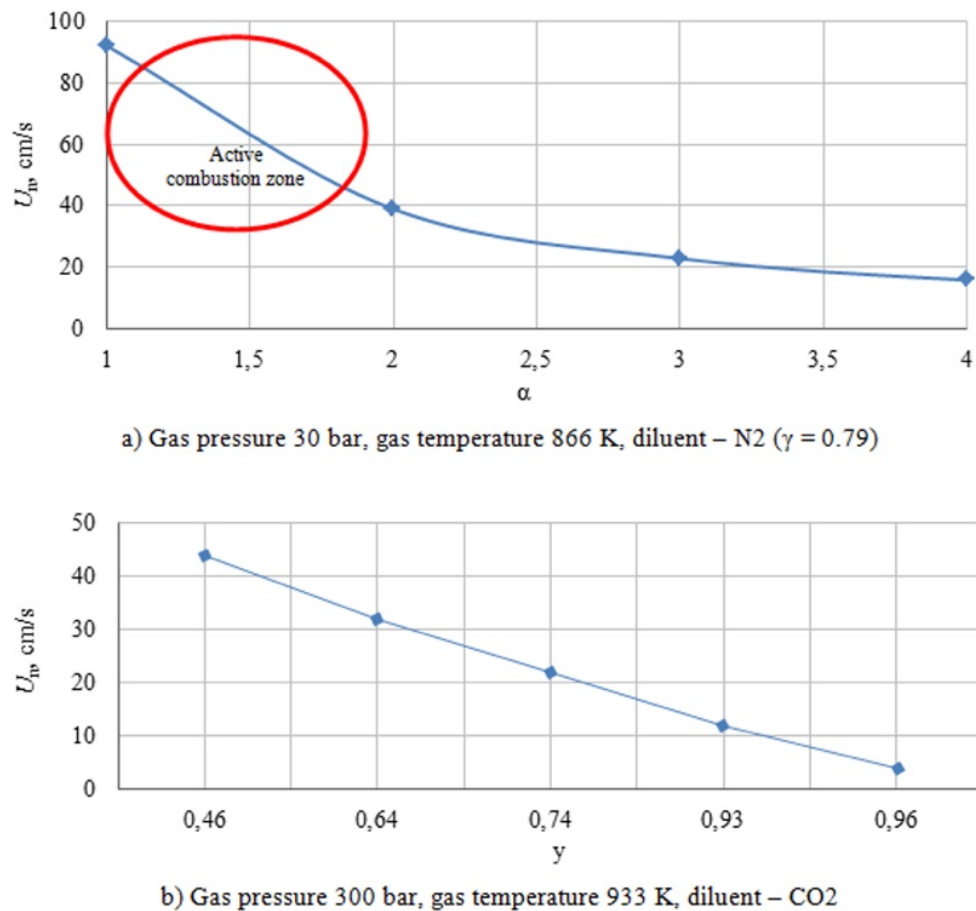


Fig. 7. Normal flame distribution velocity in the traditional and oxy-fuel cycle gas turbines.

temperature T_0 reaches the ignition border it causes a faster mixture ignition.

Ошибка! Источник ссылки не найден.a shows the normal flame propagation velocity for a traditional gas turbines combustor, pressure 30 atm and $T_{in} = 866$ K that corresponds to the compressor exit at compression up to 30 bar. **Ошибка! Источник ссылки не найден.**b demonstrates a similar velocity relation with the CO2 diluent rate γ in the oxy-fuel cycle combustor.

The **Ошибка! Источник ссылки не найден.**b results show that the flame propagation velocity in oxy-fuel cycle combustor is near to U_n of the traditional gas turbines if the CO2 diluent content in the mixture is below 0.5.

4 Discussion

The main research results are the following:

- The CO2 diluent is a stronger chemical reactions inhibitor than N2. At other conditions equal the normal flame propagation velocity in CO2 is four times smaller than the N2 diluent one, the 75% velocity reduction from 39 to 10 cm/s at the diluent content in oxidizer 79%;

- The combustor pressure increase reduces the flame propagation velocity, at the pressure increase from 20 atm up to super-critical pressure of 200 atm the reduction is 36%;

- A change in the CO2 concentration of the diluent in the mixture with the oxidizing agent in the range of the volume content from 60 to 79% leads to a decrease in the flame propagation rate by 65% (from 42.5 to 10 cm/s) at atmospheric pressure and by 94% at supercritical pressure (from 14.2 to 0.8 cm/s).

In relation with the ballasting gas content supplied together with oxidizer at CO2-O2 diluent mass contents from 0.945 to 0.460 the following parameters are determined:

- The normal flame propagation velocity verifies from 7 to 45 cm/s. A 1% reduction of the diluent content in CO2-O2 mixture increases the U_n velocity for 1.4%;

- The U_n amount for the natural gas combustion in the O2 and CO2 mixture is compatible with the traditional gas turbine combustors at the γ values from 0.47 to 0.65. This γ range corresponds to the CO2 content in the O2 + CO2 mixture in the active combustion zone below 15% of the total mass.

5 Conclusion

The investigation results show the problems concerned with transition to the new diluent and higher combustor pressure. In the oxy-fuel cycle conditions CO₂ remarkably slows the combustion process. Stable efficient methane combustion in the oxygen and carbon dioxide mixture may be reached under the following conditions:

- Carbon dioxide supply into the active combustion zone must be below 20% of its total mass flow. This flow must be split into two parts, one as a mixture with oxidizer with the γ of CO₂-O₂ mixture below 0.5, and second along the combustor walls for its cooling. This CO₂ flow split allows application of the traditional gas turbine combustor recommendations;

- The gas-fuel mixture velocity in the oxy-fuel cycle combustor must be below 20-25 m/s;

Further 3-D combustion simulation may employ the GRI-Mesh 3.0 kinetic mechanism, its calculation results fit test results with errors below 3.5%.

Acknowledgements

This study conducted by Moscow Power Engineering Institute was financially supported by the Ministry of Science and Higher Education of the Russian Federation (project No. FSWF-2020-0020).

References

- [1] F. Weizhong, The research on design and technology of new high efficiency supercritical unit – a kind of cross-compound steam turbine generator unit in a manner of elevated and conventional layout, Proceedings of the 2-nd IEA CCC Workshop on Advanced Ultras-Supercritical Coal-Fired Power Plants, Rome, Italy (2014)
- [2] S. Martin, B. Forrest, N. Rafati, X. Lu, J. Fetvedt, M. McGroddy, D. Freed, Progress update on the Allam cycle: commercialization of NET Power and the NET Power Demonstration Facility, Proceedings of the 14-th Greenhouse Gas Control Technologies Conference, Melbourne, Australia (2018)
- [3] A.B. Amato, P.D. Hudak, D. Carlo, D. Noble, J. Scarborough, T. Seitzman, T. Lieuwen, Methane oxy-combustion for low CO₂ cycles: Blowoff measurements and analysis, Journal of Engineering for Gas Turbines and Power **133**, 6 (2011)
- [4] S. Suzuki, Y. Iwai, M. Itoh, Y. Morisawa, P. Jain, Y. Kobayashi, High pressure combustion test of gas turbine combustor for 50MWth supercritical CO₂ demonstration power plant on Allam cycle, Proceedings of the International Gas Turbine Congress, Tokyo, Japan (2019)
- [5] A. Alenezi, J.S. Kapat, Thermodynamic analysis of CO₂ Allam cycle for concentrated solar power complemented with oxy-combustion, Proceedings of AIAA Propulsion and Energy Forum, Indianapolis, Indiana, USA (2019)
- [6] I.L. Polezhaev, V. Yu, Normal flame propagation speed and analysis of the influence of system parameters on it, Thermophysics of high temperatures **43**, 6, 933–942 (2005)
- [7] E.L. Petersen, M. Röhrig, D.F. Davidson, R.K. Hanson, C.T. Bowman, High-pressure methane oxidation behind reflected shock waves, Proceedings of the Symposium (International) on Combustion **26**, 1, 799–806 (1996)
- [8] A.H. Lefebvre, *Gas turbine combustion: Alternative fuels and emissions* (Boca Raton: CRC Press, 557, 2010)
- [9] G. Kim, Y. Kim, Y.J. Joo, Conditional moment closure for modeling combustion processes and structure of oxy-natural gas flame, *Energy & Fuels* **23**, 9, 4370–4377 (2009)
- [10] B.T. Chorpene, K.H. Casleton, G.A. Richards, M. Woike, B. Willis, Stoichiometric oxy-fuel combustion for power cycles with CO₂ sequestration, Proceedings of the 3-rd Joint Meeting of the US Sections of the Combustion Institute, Chicago, Illinois, USA (2003)
- [11] S. Coogan, X. Gao, A. McClung, W. Sun, Evaluation of kinetic mechanisms for direct fired supercritical oxy-combustion of natural gas, Proceedings of the Turbomachinery Technical Conference and Exposition, Seoul, South Korea (2016)
- [12] V.P. Zhukov, V.A. Sechenov, A.Y. Starikovskii, Spontaneous ignition of methane-air mixtures in a wide range of pressures, Combustion, Explosion and Shock Waves **39**, 5, 487–495 (2003)
- [13] M.D. Smooke, *Reduced kinetic mechanisms and asymptotic approximations for methane-air flames: A topical volume* (Berlin: Springer-Verlag, 245, 1991)
- [14] N. Slavinskaya, M. Braun-Unkloff, P. Frank, Reduced reaction mechanisms for methane and syngas combustion in gas turbines, Journal of Engineering for Gas Turbines and Power **130**, 2, 021504 (2008)
- [15] H. Wang, X. You, A.V. Joshi, S.G. Davis, A. Laskin, F. Egolfopoulos, C.K. Law, USC Mech Version II, High-temperature combustion reaction model of H₂/CO/C₁-C₄ compounds (2007) [Electronic resource]. Available at: http://ignis.usc.edu/Mechanisms/USC-Mech%20II/USC_Mech%20II.htm
- [16] D. Healy, D.M. Kalitan, C.J. Aul, E.L. Petersen, G. Bourque, H.J. Curran, Oxidation of C₁-C₅ alkane quaternary natural gas mixtures at high pressures, *Energy & Fuels* **24**, 3, 1521–1528 (2010)
- [17] X. Gao, S. Yang, W. Sun, A global pathway selection algorithm for the reduction of detailed chemical kinetic mechanisms, Combustion and Flame, 167, 238–247 (2016)
- [18] A. Frassoldati, T. Faravelli, E. Ranzi, The ignition, combustion and flame structure of carbon monoxide/hydrogen mixtures, Note 1:

- Detailed kinetic modeling of syngas combustion also in presence of nitrogen compounds, *International Journal of Hydrogen Energy* **32**, 15, 3471–3485 (2007)
- [19] W.P. Fan, Y. Gao, Y.M. Zhang, C.L. Chow, W.K. Chow, Experimental studies and modeling on flame velocity in turbulent deflagration in an open tube, *Process Safety and Environmental Protection* **129**, 291–307 (2019)
- [20] G. Gai, S. Kudriakov, B. Rogg, A. Hadjadj, E. Studer, O. Thomine, Numerical study on laminar flame velocity of hydrogen-air combustion under water spray effects, *International Journal of Hydrogen Energy* **44**, 31, 17015–17029 (2019)