Staged, High Pressure Oxy-Combustion Technology: Development and Scale-Up

DE-FE0009702

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2017 NETL CO_2 Capture Technology Project Review Meeting
Aug. 25, 2017

Washington University in St. Louis

CONSORTIUM FOR CLEAN COAL UTILIZATION

Project Overview

Project Objectives: Phase II

Design and build a laboratory-scale facility and conduct laboratory-scale experiments and complimentary modeling that address the technical gaps and uncertainties addressed in Phase I.

Advance SPOC technology to TRL-5.

Funding

Total project (Phases I & II): $5,243,789
- DOE share: $4,137,184
- Cost share: $1,106,614

Project Performance Dates

10/01/2012 - 09/30/2017 (extended)

Project Participants

Washington University – Lead: SPOC development, experiments
EPRI – Technology evaluation, end-user insight, corrosion
ORNL – Corrosion study

Technology Background

Pressurized Oxy-Combustion

- The requirement of high pressure CO_2 for sequestration enables pressurized combustion as a tool to increase efficiency and reduce costs.

- Benefits of Pressurized Combustion
  - Recover latent heat in flue gas
  - Latent heat recovery can be combine with integrated pollution removal
  - Reduce gas volume
  - Avoid air-ingress
  - Higher partial pressure of O_2
  - Optically dense atmosphere

Motivation for SPOC

Key Features:

Improve capital costs by:

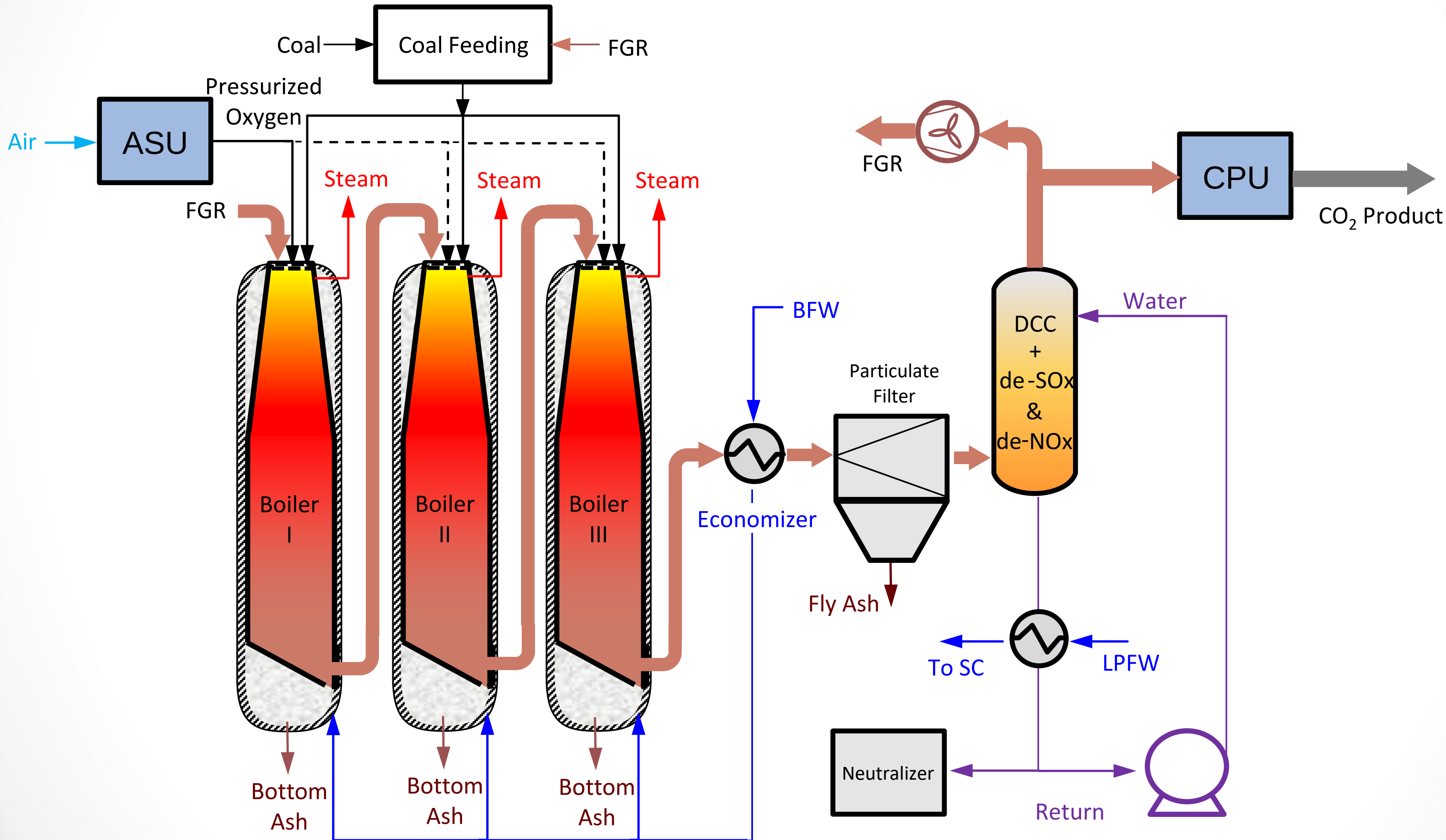
- Optimizing use of radiation to minimizing heat transfer surface area
- Minimizing recycled flue gas (RFG)
- Minimizing equipment size
- Utilizing modular boiler construction

Improve operating costs by:

- Maximizing plant efficiency
  - Low FGR
  - Dry feed
  - Minimizing oxygen requirements
- Utilizing "lead chamber" process for SOx & NOx removal
- Increasing performance of wet, low BTU fuels

SPOC Process Flow Diagram

For a 550 MW_e power plant with > 90% CO_2 capture



courtesy of EPRI

Modeling parameters from DOE/NETL Guidelines

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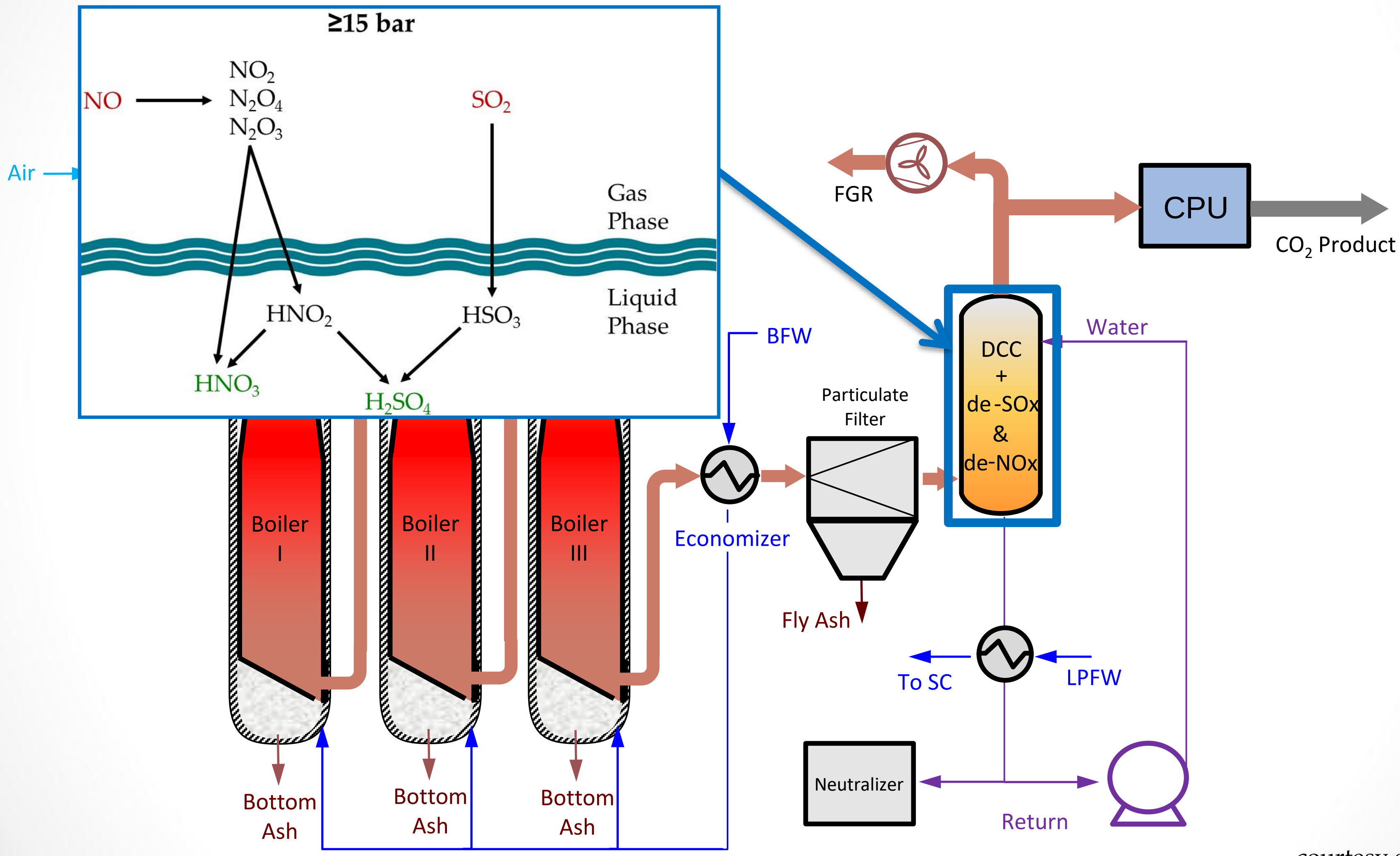


courtesy of EPRI

Modeling parameters from DOE/NETL Guidelines

Plant Efficiencies

a) supercritical steam conditions, net power output = 550 MW

	Air-fired	Atmos. P oxy-combustion	SPOC	
Coal type	Illinois #6	Illinois #6	Illinois #6	PRB
Net generating efficiency, HHV (%)	39.3	29.3	36.7	35.7

b) independent study comparing two pressurized oxy-combustion processes

	Air-fired	Atmos. P oxy-combustion		Pressurized oxy-combustion	
		(conservative)	(optimized)	ISOTHERM	SPOC
Net generating efficiency, LHV (%)	46.1	36.1	39.1	38.4	42.3

- *25% improvement in plant efficiency over first-generation oxy-combustion*

a. Gopan, A. et al. (2014) Applied Energy, 125, 179-188.

b. Hagi, H.,et al. (2014). Energy Procedia, 63, 431-439.

Technical Approach/Project Scope

Work Plan

Tasks

1. Project management
2. Design, fabrication and installation of high pressure combustion furnace
3. High pressure combustion experiments (heat flux, temp, ash, deposition)
4. Materials corrosion studies (high O_2 and SO_2 environments)
5. Modeling direct contact cooler
6. Re-evaluation of burner/boiler design
7. Update process model and techno-economic analysis

Projected Phase 2 Outcomes

- Proof of concept demo of coal combustion under SPOC conditions.
- Improved understanding of radiation heat transfer in pressurized oxy-combustion conditions
- Improved understanding of ash formation/deposition mechanism in pressurized oxy-combustion conditions
- Knowledge of performance of boiler tube materials under SPOC conditions
- Improved estimate of SOx, NOx removal efficiency in direct contact cooler
- Reduced uncertainty and contingencies → improved COE

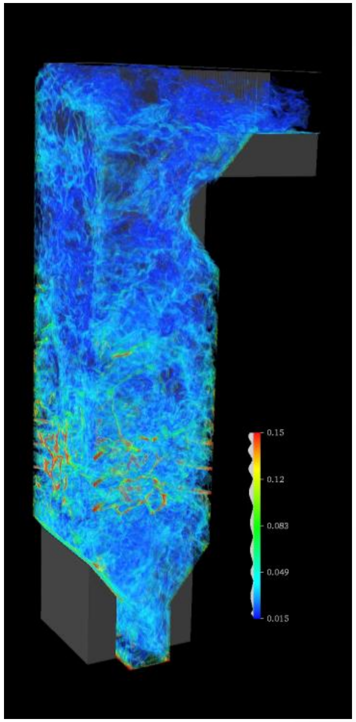
Progress and Current Status:

Key Considerations for Improved Low-Recycle Pressurized Oxy-Combustion Burner-Combustor

- High pressure
  - Pressure vessel – cylindrical: high aspect ratio.
  - Requires distribute heat release.
  - Requires control of soot formation.

- Low-recycle (high T flame)
  - Avoid flame impingement.
  - Avoid excessive heat flux
  - Control oxygen concentration near boiler tubes.
  - Control soot formation.

- Minimize ash deposition (fouling & slagging).
- Ensure resilience to variations in flow conditions.
- Obtain high turn-down operation.



Courtesy of Phil Smith
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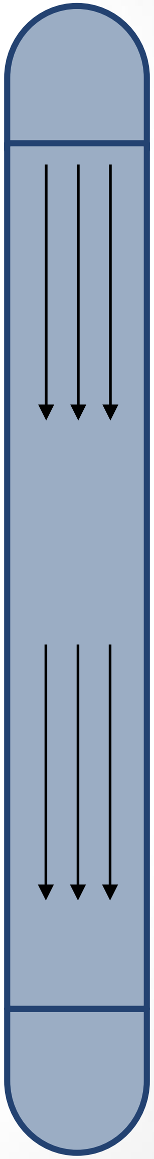
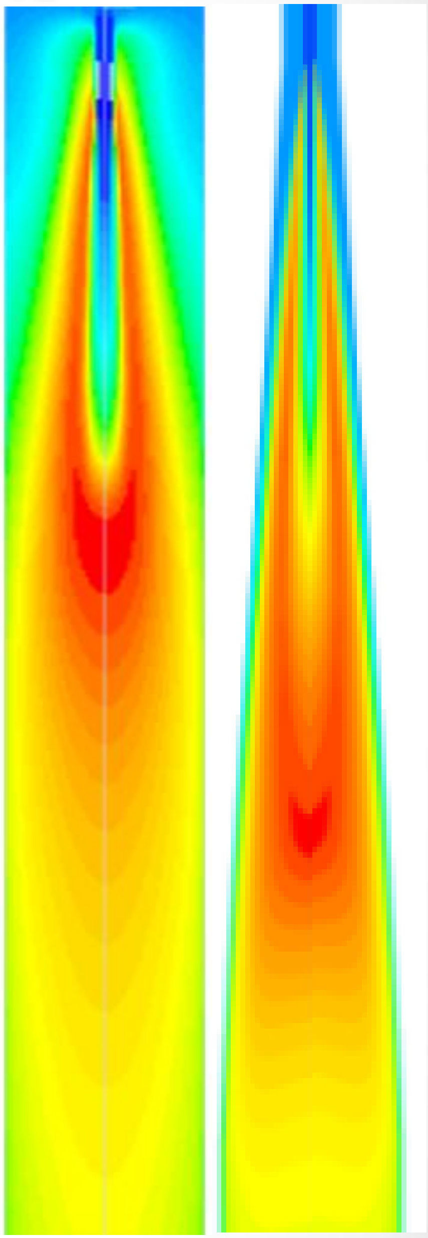


Reduce Buoyancy Effects



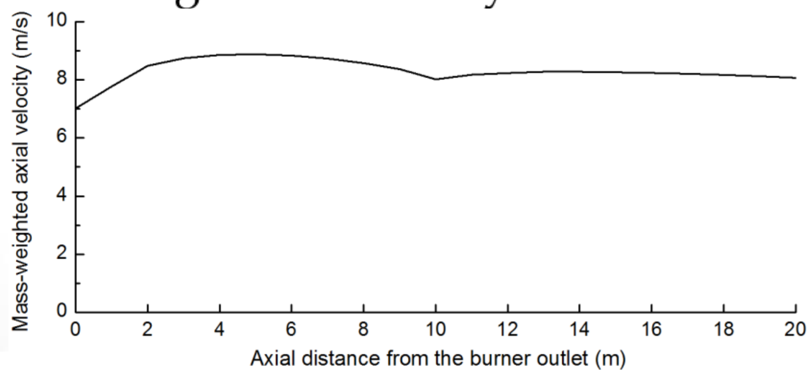
- Richardson number—buoyancy vs convection. $Ri_x = g\beta(T_{hot} - T_{surr})\frac{x}{v^2}$

- Option 1. Shrink diameter to increase v –loose heat transfer surface area.

- Q_{gas} increases due to 1) increase in T, & 2) gas generation via $C(s) \rightarrow CO_2\,(g)$

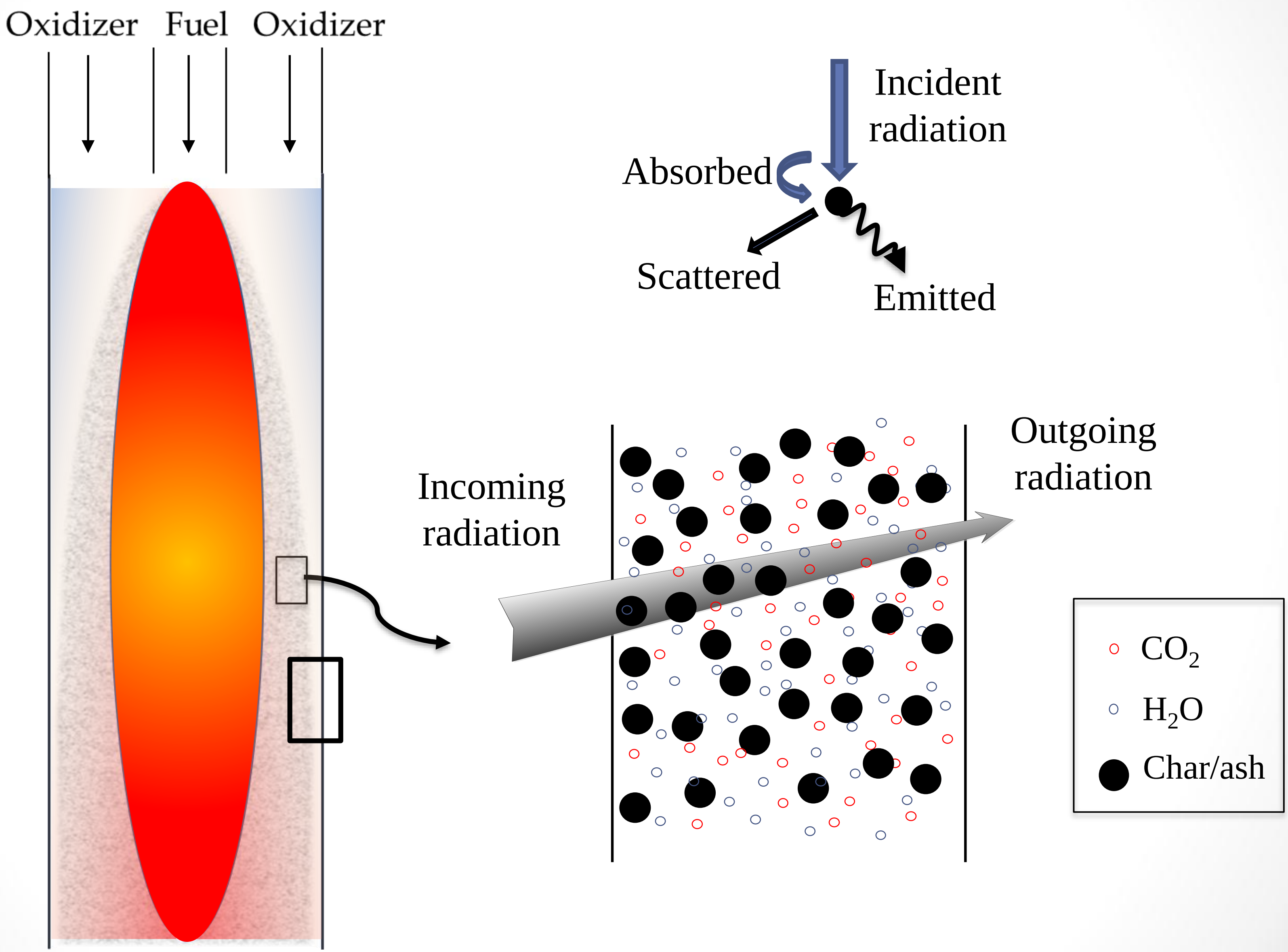
- Option 2. Reduce inlet size of reactor—increase axial velocity.

- Tapered design-low Ri everywhere.



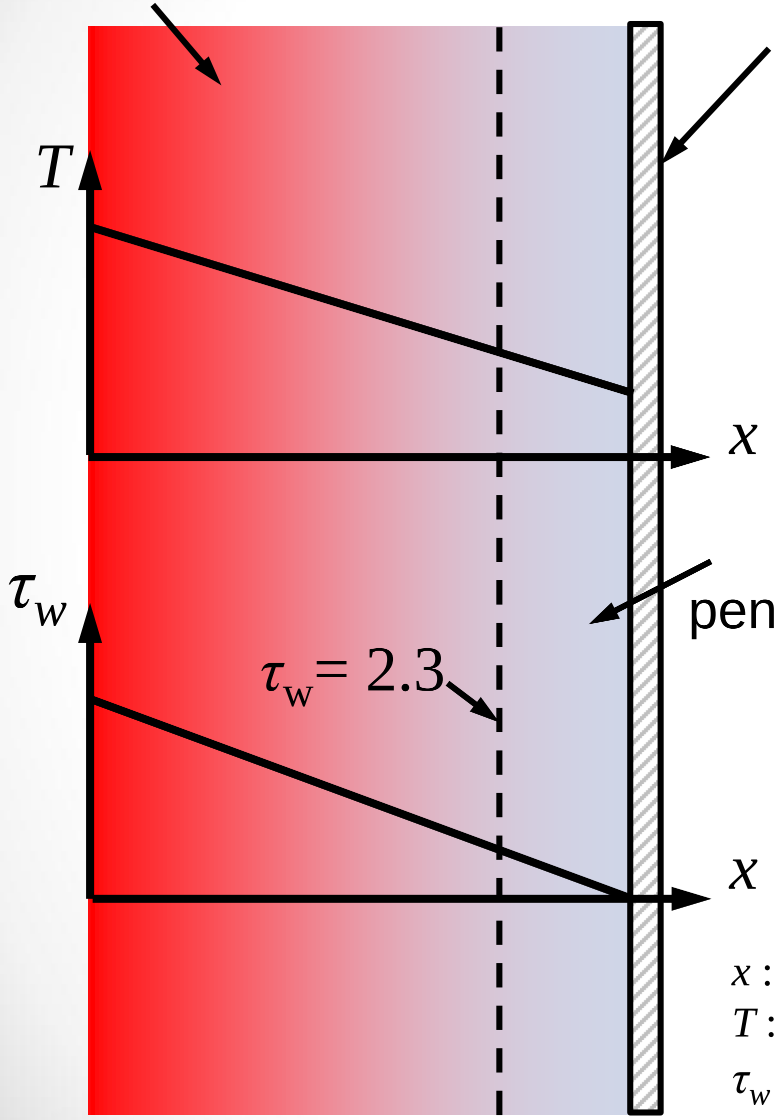
Xia, F. (2014); Gopan, A. et al. (2017a, in review)

Radiation in axial flow combustion



Adapted from Xia, et al. (2016)

Radiative Trapping



At high pressure:

- Optically dense medium.
- Wall heat flux only dependent on the temperature distribution in the radiation penetration layer (δ_{RP}).

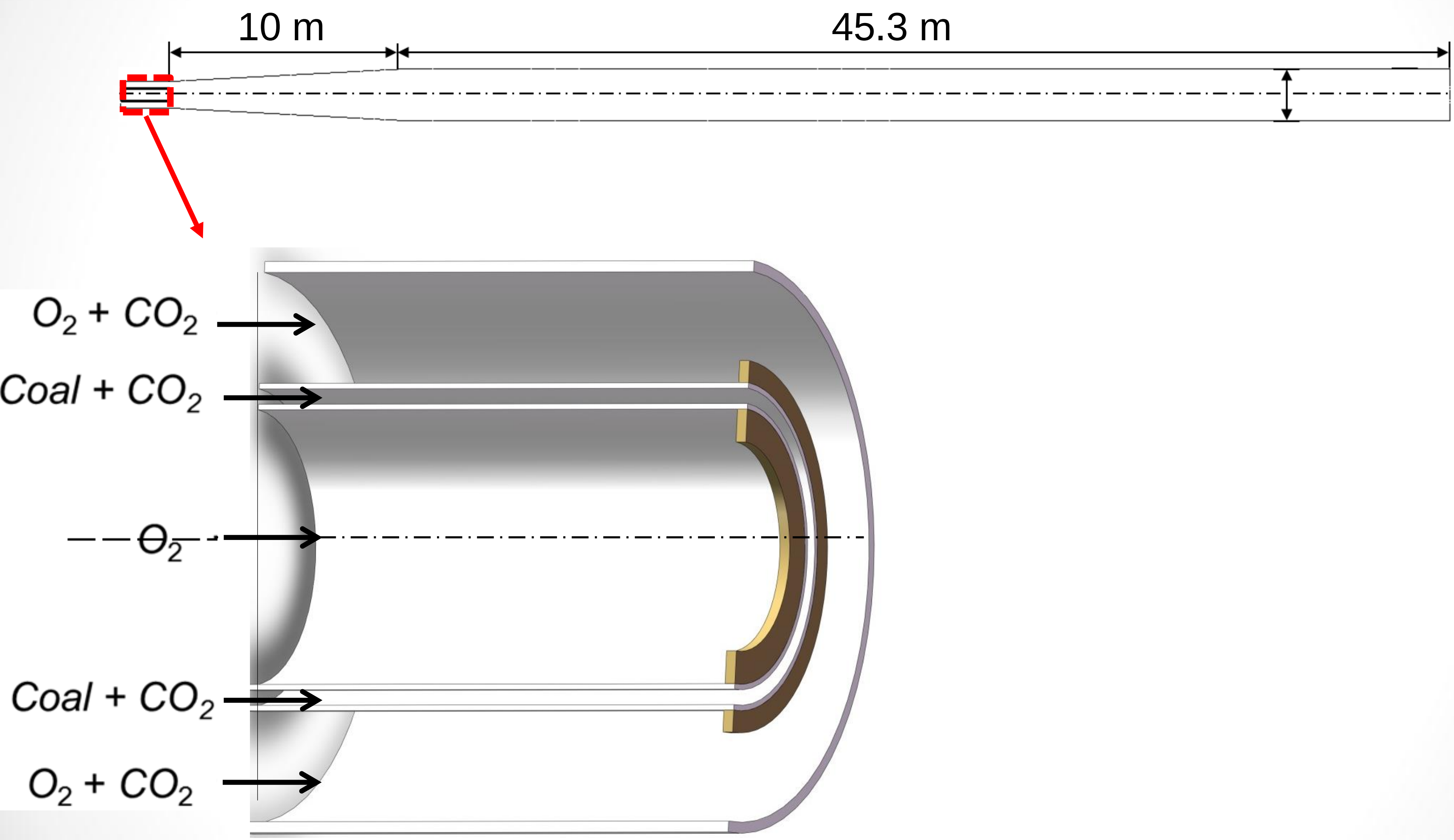
$$-\ln\left(\frac{I}{I_0}\right) = \tau_w(x) = \int_x^{x_w} [N_p(x) c_{ext}(d_p)] dx$$

($\tau_w = 2.3$; *transmissivity* $\approx$ *10%*)

x : Distance from the wall
T : Temperature
τ_w : Optical thickness from the wall

Gopan et al. (2017a in review); Xia et al. (2016)

Burner/Boiler Design



Gopan et al. (2017a in review)

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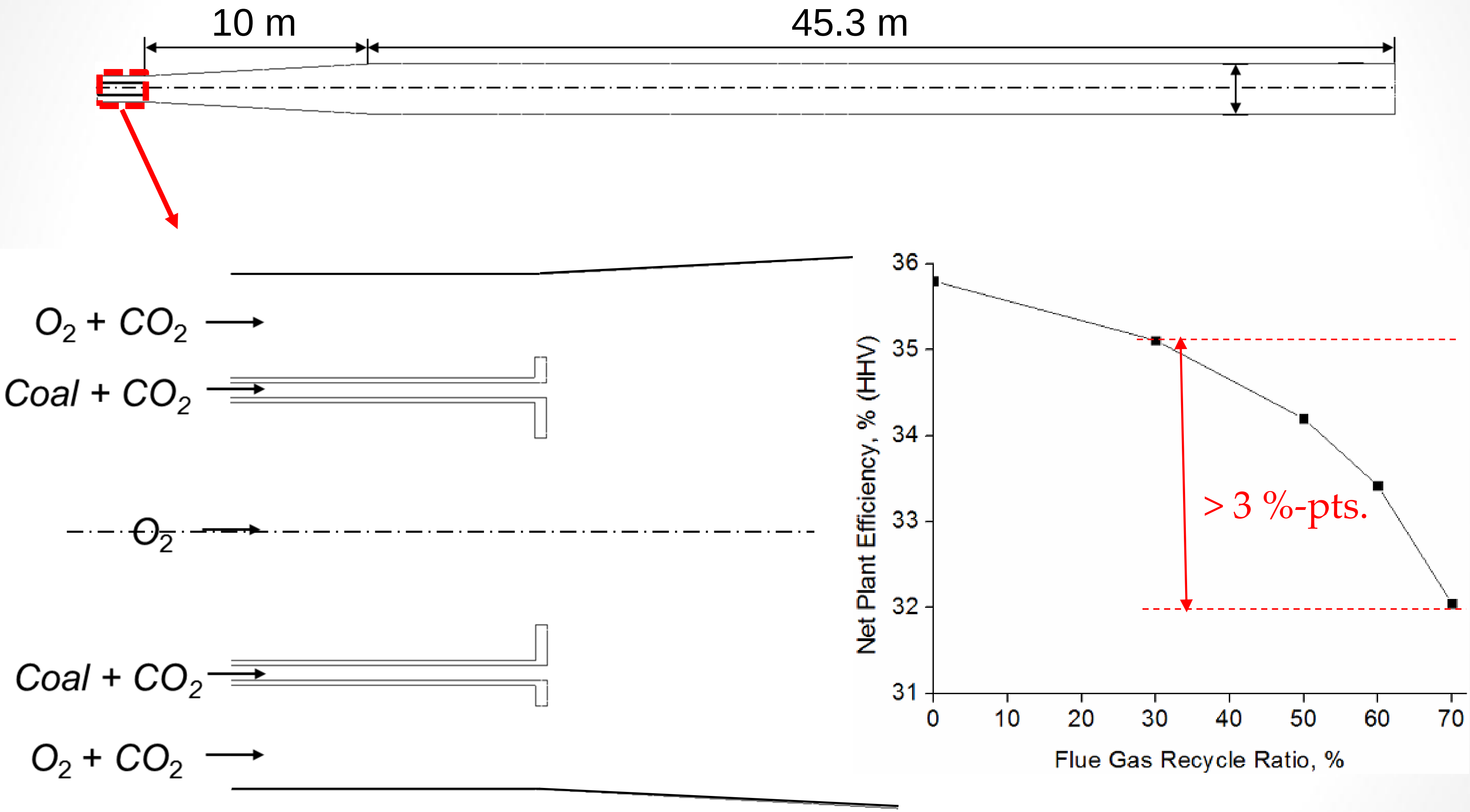
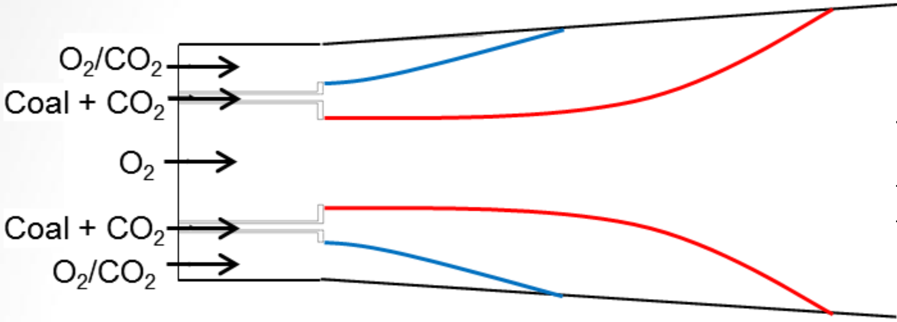


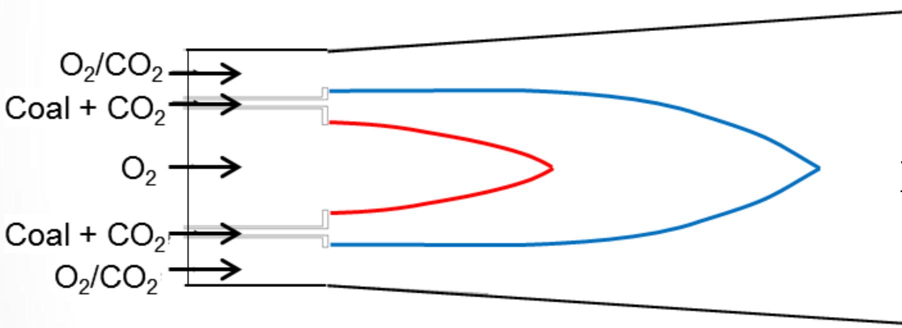
Gopan et al. (2017a in review)

Central-Oxygen Burner – Flame Shapes

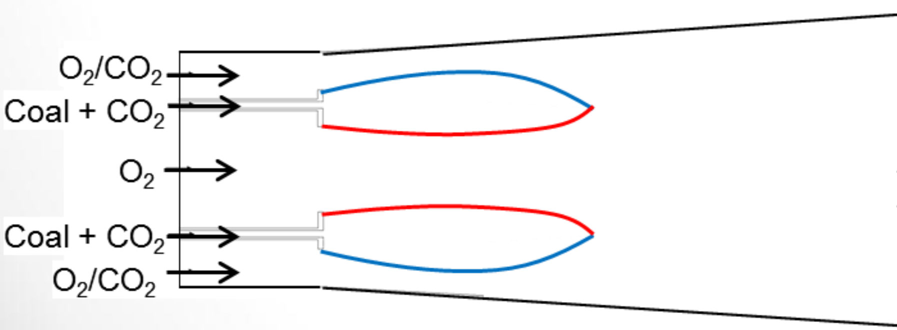
Three main flame shapes with an over-ventilated triaxial flame:



Unacceptable
Flame impingement – high heat flux



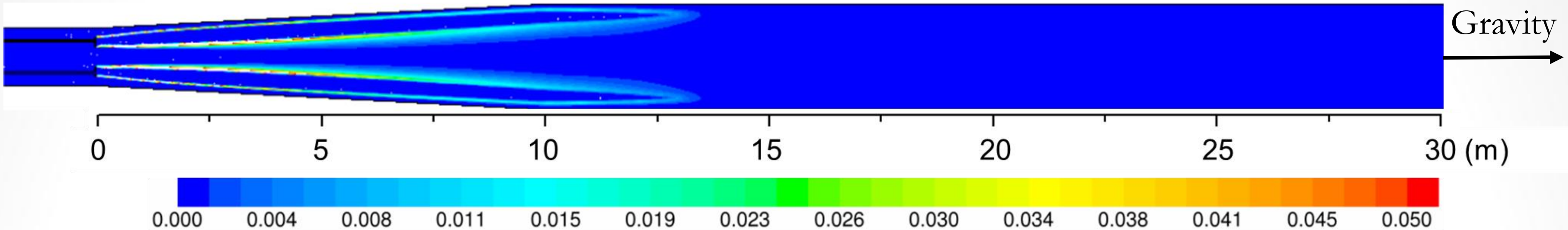
Acceptable
But low central oxygen => more recycle



Preferable solution

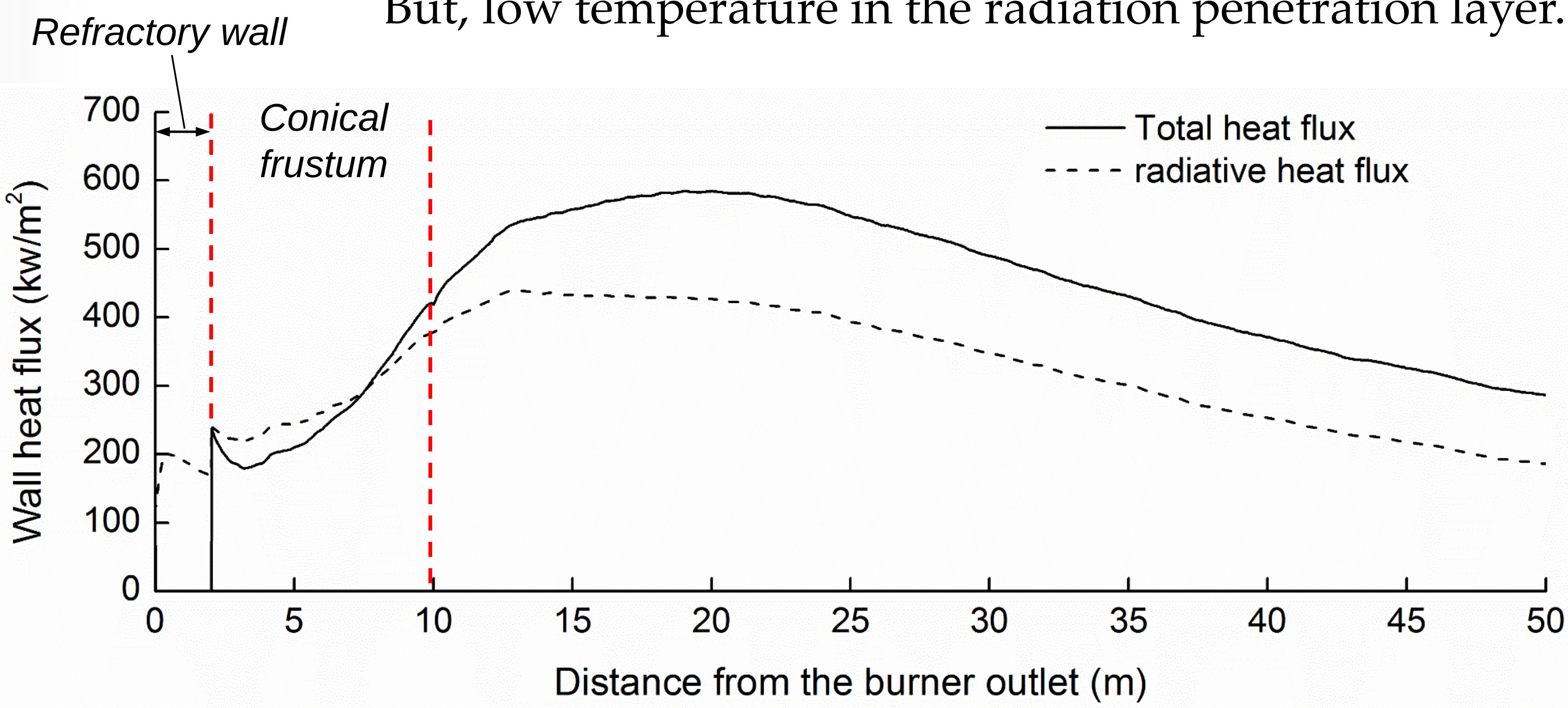
Gopan et al. (2017a in review)

SPOC Boiler Results



SO $[O_2]$ = 35 vol.%

High temperature in the core of the boiler
But, low temperature in the radiation penetration layer.



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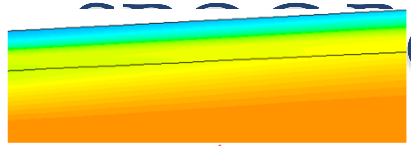

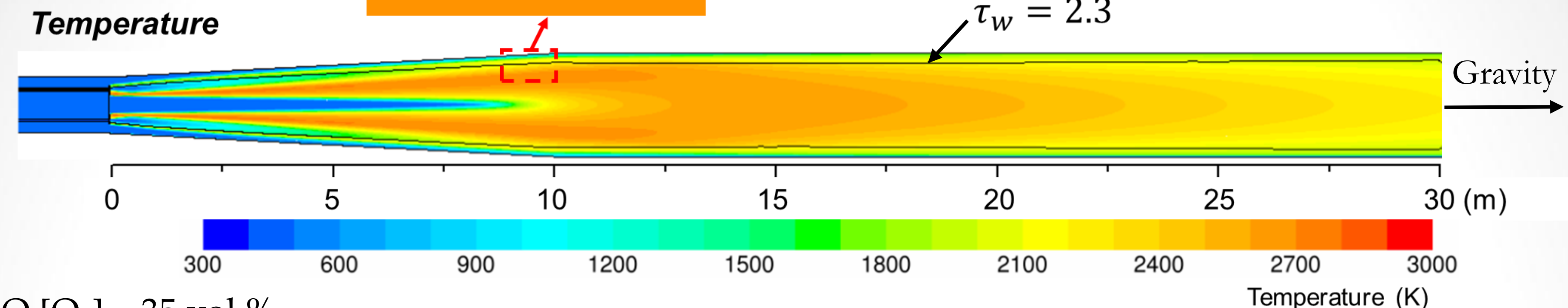

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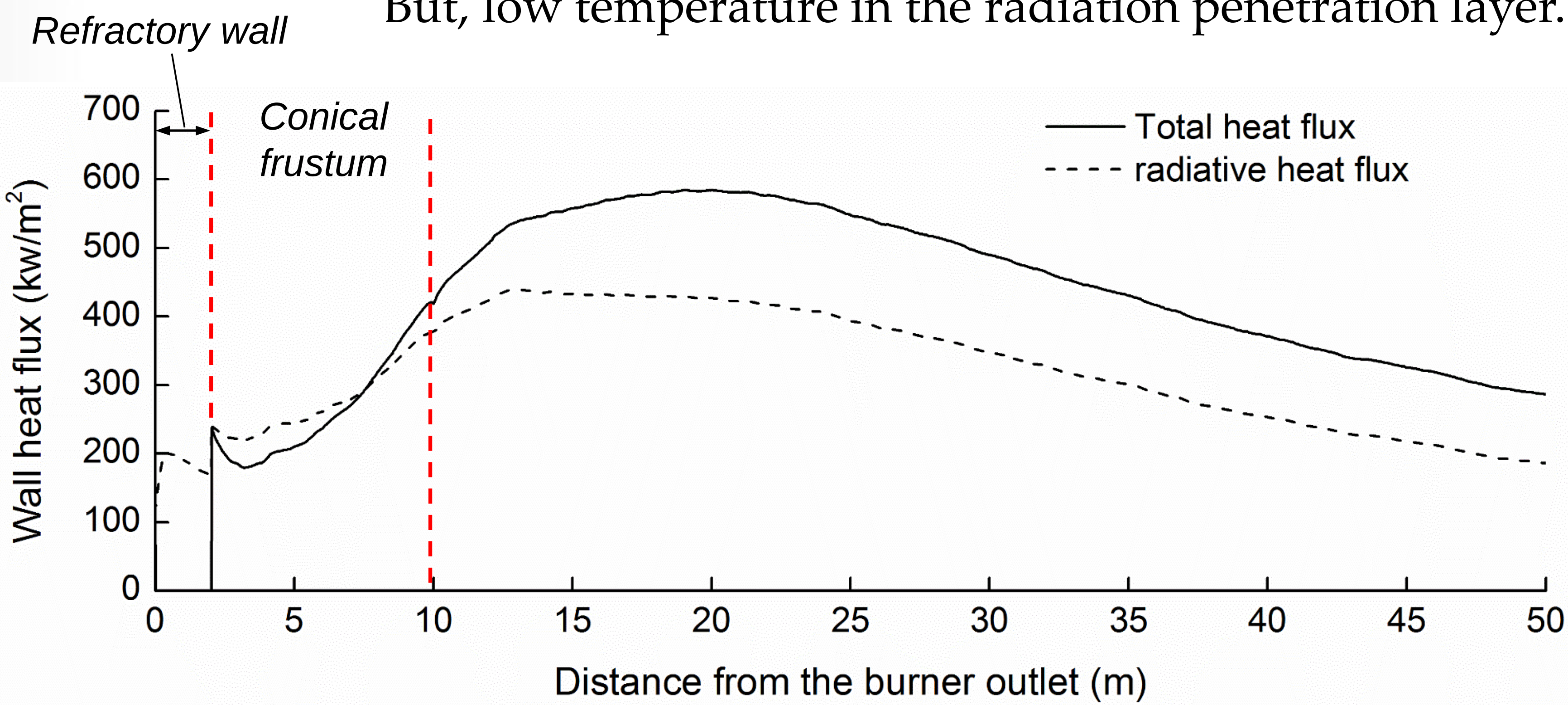
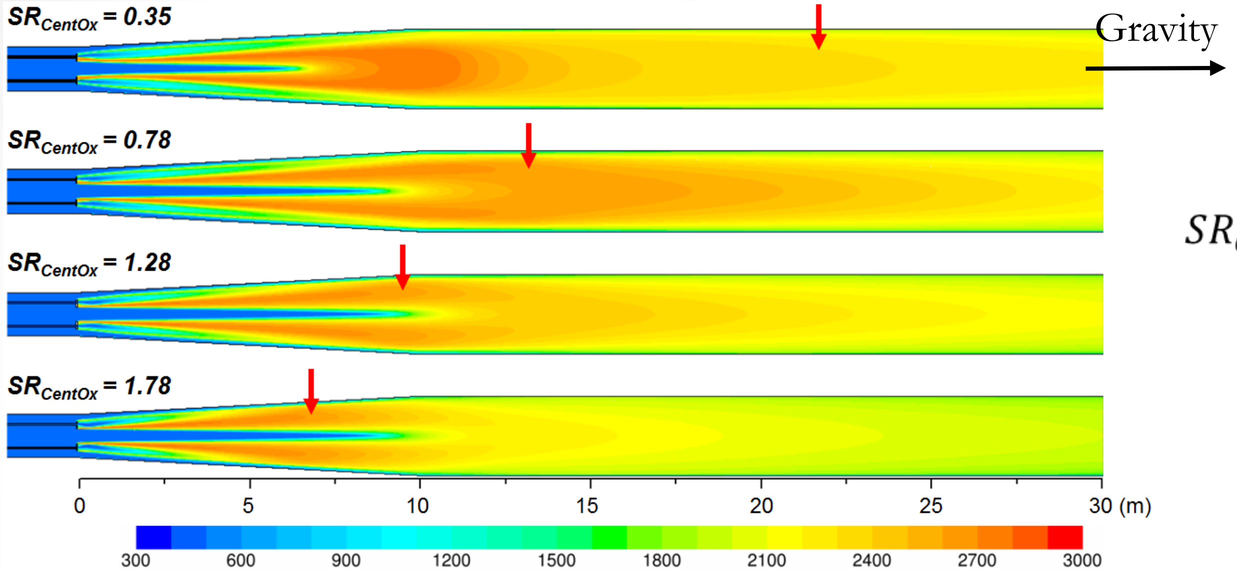
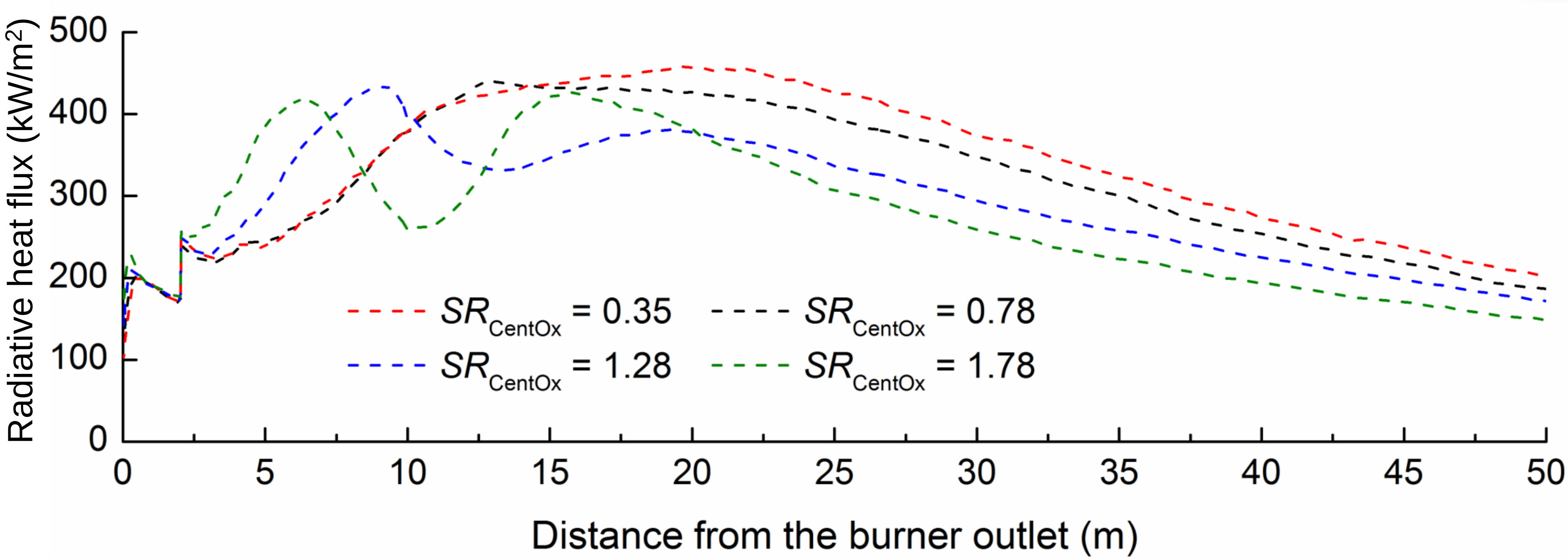


Effect of Mixing – Central Oxygen Flow

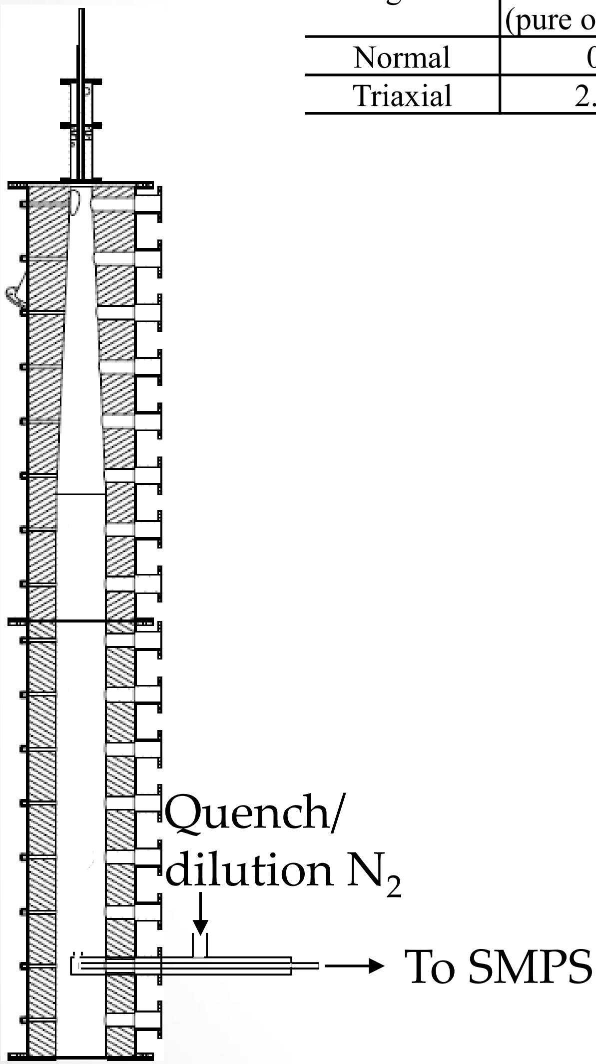


$$SR_{CentOx} = \frac{Central\ O_2\ Supplied}{Total\ O_2\ Required}$$



Soot Comparison – Normal vs. Tri-axial

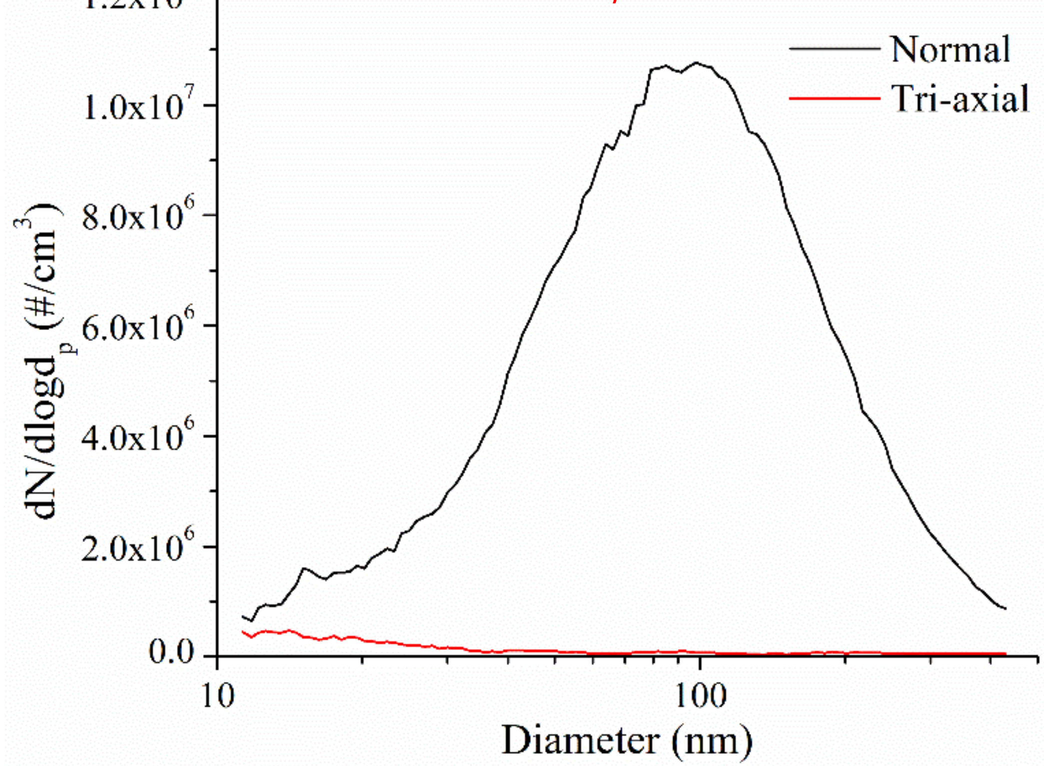
Configuration	IO Flow (m^3/h)[a] (pure oxygen)	Fuel stream flow (m^3/h)[a]	Fuel stream [CH_4] (%v)	SO Flow (m^3/h)[a]	SO Stream [O_2] (%v)	SR_{IO}	SR_{Total}
Normal	0	3.1	62.7	19.7	45.5	0	2.3
Triaxial	2.7	3.1	62.7	17.0	36.8	0.7	1.6



Total # concentration:

Normal: 1×10^6 #/cm^3

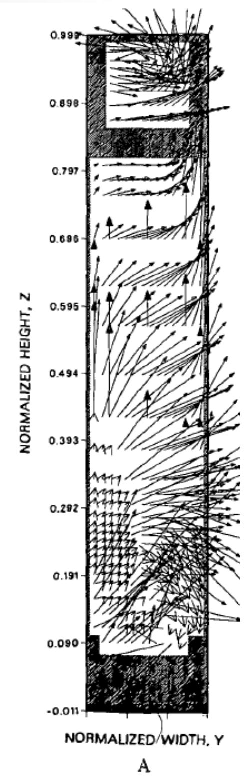
Tri-axial: 1×10^4 #/cm^3

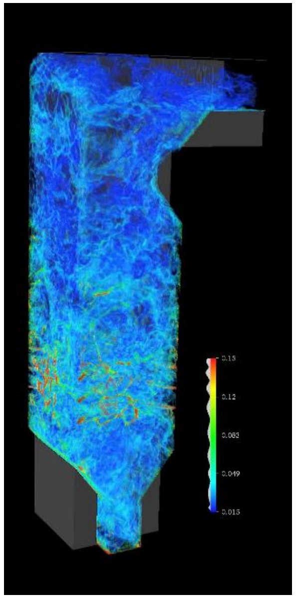


Particle Deposition in Conventional and SPOC Boilers

High-mixing traditional systems

Wall-fired T-fired





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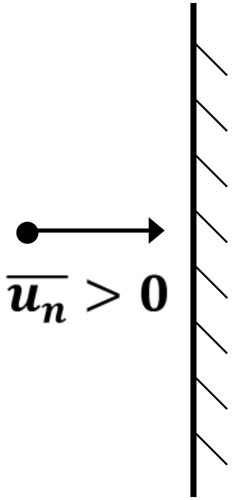
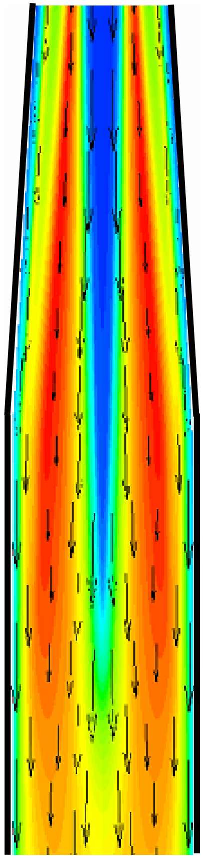
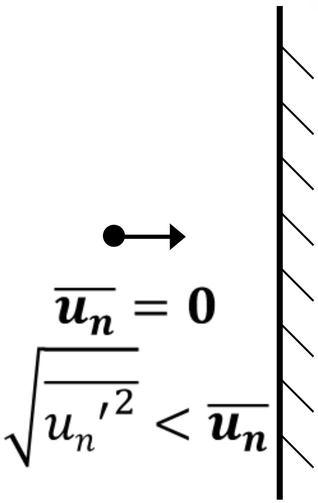


Inertial impaction is dominant

Low-mixing, axial flow SPOC

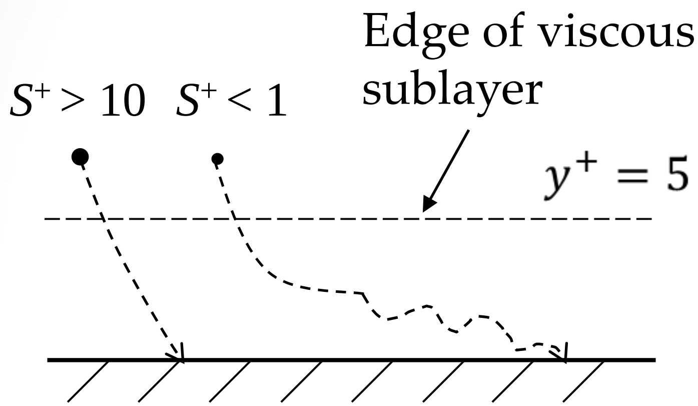




Eddy impaction & thermophoresis dominant

Deposition temp. in non-isothermal flows

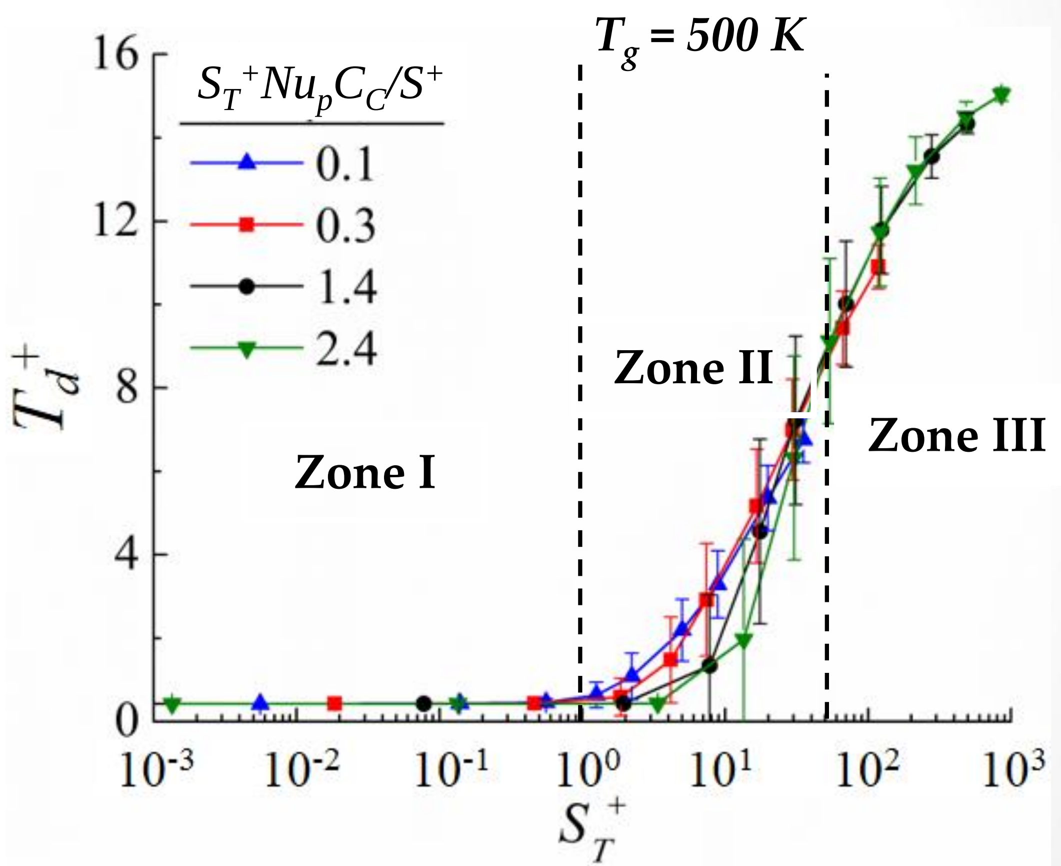
- Non-dimensional deposition temperature[1] $T_d^+ = \frac{\rho_g c_{p,g} u_* (T_d - T_w)}{\dot{q}}$



S^+ determines residence time

S_T^+ determines cooling speed

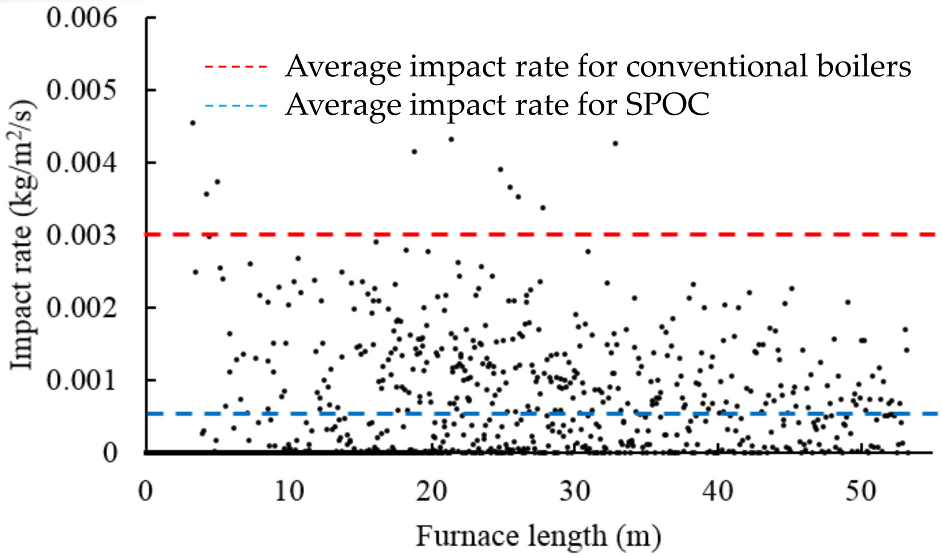
$$T_d^+ = f(S^+, S_T^+)$$

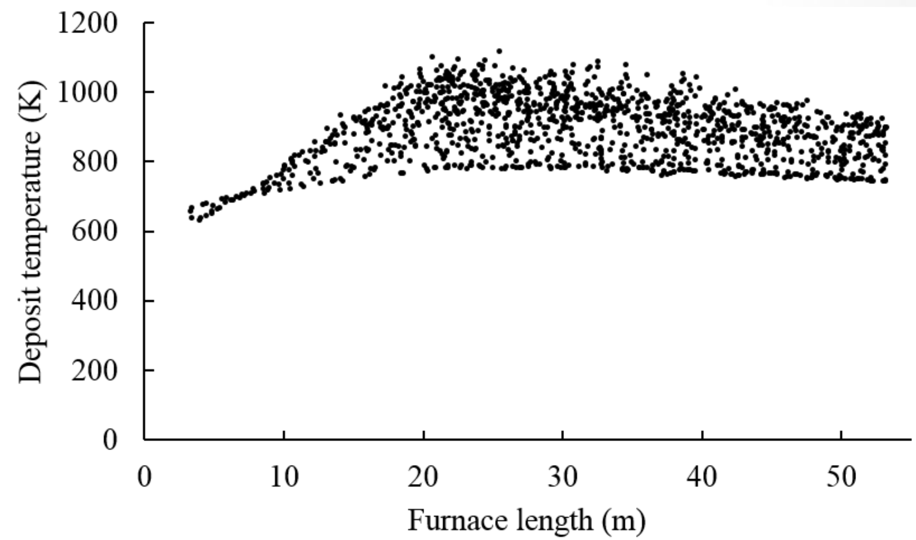


[1] B. Kader 1981

SPOC particle deposition

- CFD simulation results





- The average particle impact rate in the SPOC boiler is an order of magnitude lower than that in conventional PC boilers[1]
- The temperatures of all ash deposits are lower than 850 ^{o}C, which is much lower than the ash fusion temperature. Slagging is unlikely.[2]

[1] Wang, H., & Harb, J. N. (1997) *Progress in Energy and Combustion Science, 23*(3), 267-282.

[2]Yang et al. (2017 in prep); Gopan et al. (2017c in prep);

Pressurized Oxy-Combustion Facility

Objectives:

- ~100 kW test under SPOC conditions
- Wide operating range, pressure 1-15 bar, oxygen concentration 21~100%

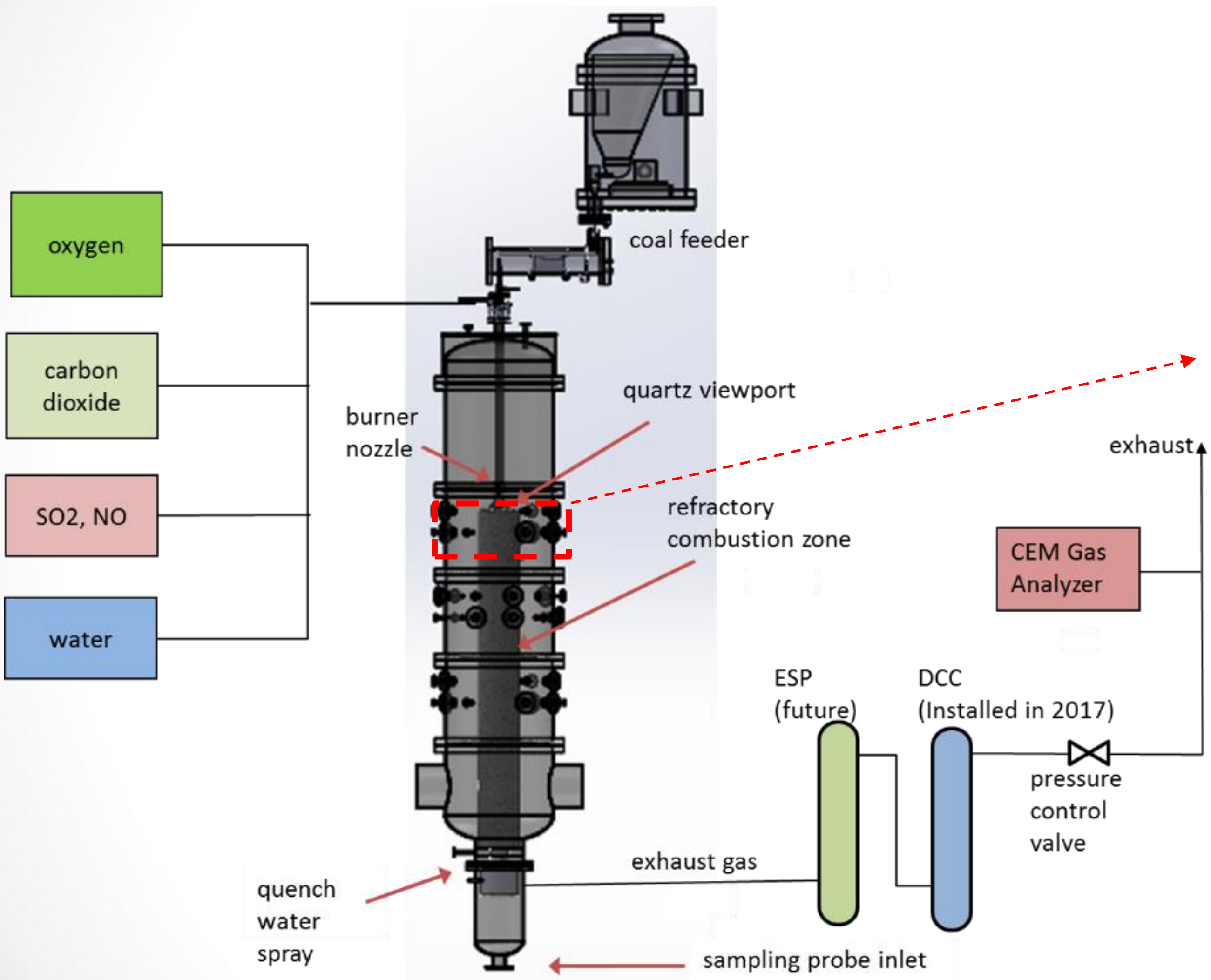
Capabilities:

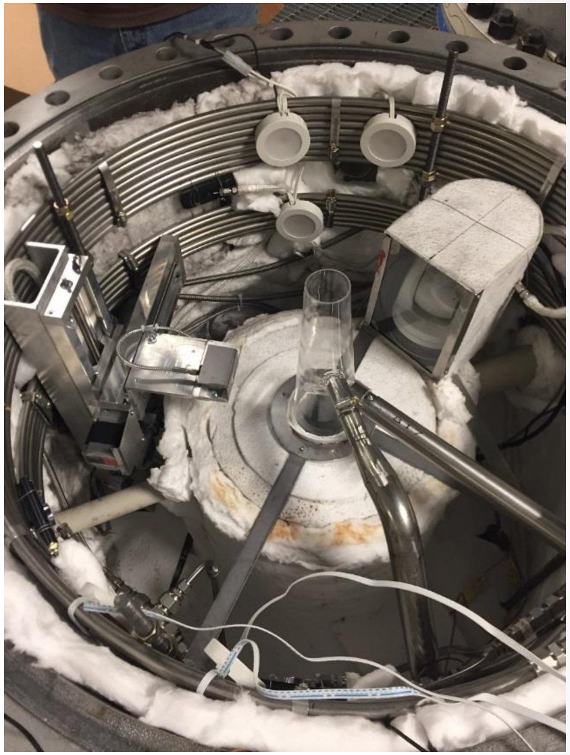
- Visual access of flame shape
- Laser diagnostics
- High-speed, high-resolution camera
- Heat flux sensors
- Pressurized sampling (gas & particle)
    - CEMS, FTIR, SMPS, ELPI

DOE U.S.-China CERC CCCU

Washington University in St.Louis

Pressurized Oxy-Combustion Facility





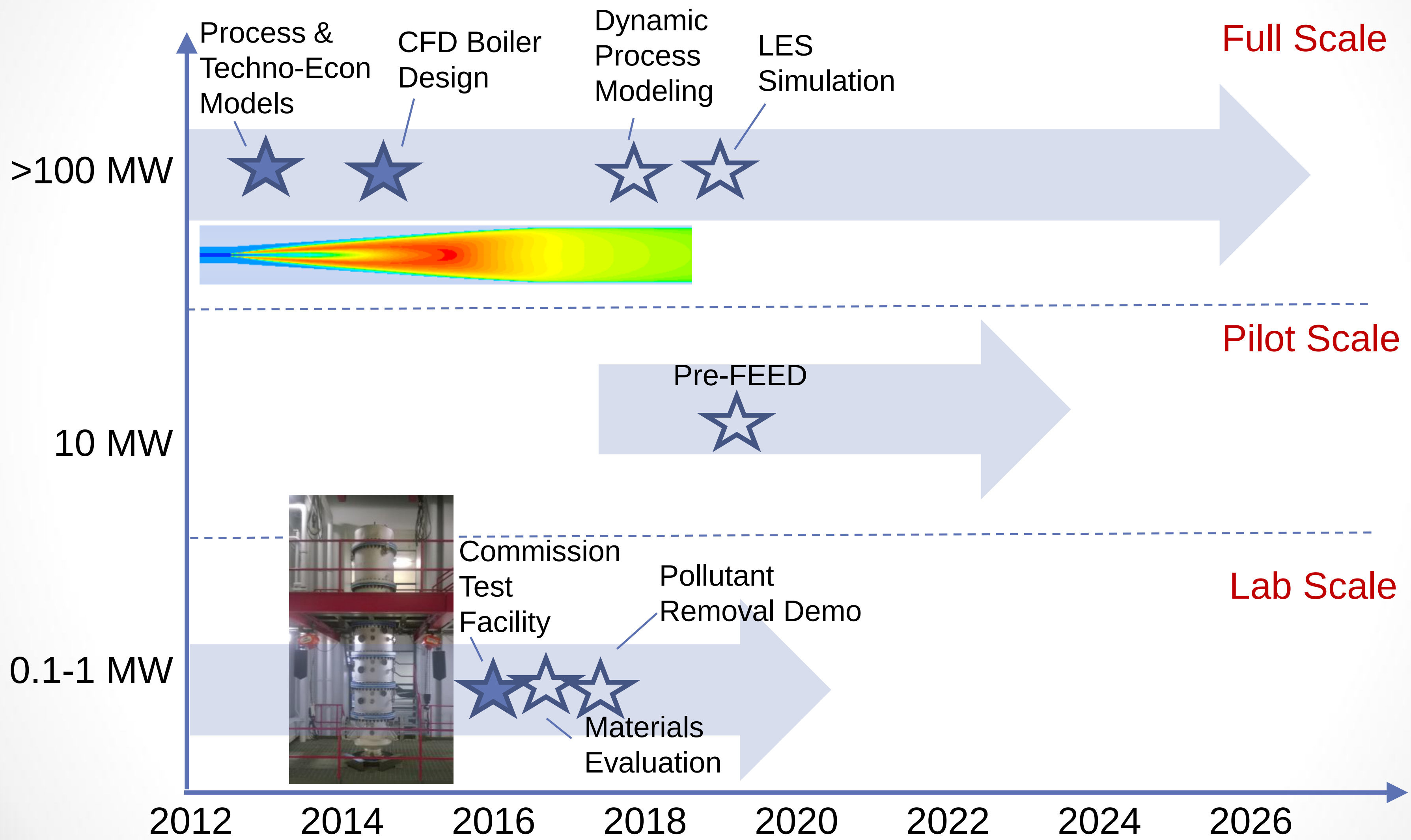
High-Speed Video

SPOC Status

Next steps:

- U.S.-China Clean Energy Research Center (CERC-ACTC)
  - Increasing scale of existing facility
  - Advancing technology to Pre-FEED for pilot scale facility
- Integrated Flue Gas Purification and Latent Heat Recovery for Pressurized Oxy-Combustion, DE-FE0025193
  - Will discuss in next talk
- Enabling Staged, Pressurized Oxycombustion: Improving Flexibility and Performance at Reduced Cost DE-FE0029087
  - EPRI (Lead), Doosan Babcock, Air Liquide and WUSTL

Development Roadmap



Acknowledgements

Wash U: A. Gopan, F. Xia, B. Kumfer, Z. Yang, A. Adeosun, D. Khatri, T. Li
EPRI: J. Phillips, D. Thimsen, S. Hume, S. Kung, J. Shingledecker
ORNL: B. Pint

Funding:
U.S. Department of Energy: Award # DE-FE0009702
Advanced Conversion Technologies Task Force, Wyoming
Consortium for Clean Coal Utilization, Washington University in St. Louis
Sponsors: Arch Coal, Peabody Energy, Ameren

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