Numerical Investigation into Biomass Gasification using Fluidized Bed Gasifier

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Presentation Outline

- Introduction
- Model development
- Simulation procedure
- Results
- Conclusion & outlook

Introduction

- Renewed interest in biomass gasification!
  1. Scarcity of conventional fuels & price hikes
  2. Fluctuations in supply & environmental concerns
  3. Increased energy demand due to population explosion
- Biomass sources are abundant e.g. animal & municipal wastes, agricultural residues
- Need to develop functional & competitive technology
- CFD modeling is effective in design and development

Biomass gasification

- Biomass gasification converts biomass into a more convenient gaseous fuel
- Main product of gasification process is syn gas (comprising H_2 , CO , CO_2 , CH_4, H_2O, N_2)
- Syn gas can be used in boilers, engines, and turbines

Classification of Gasifiers

- Fixed bed
  - Up draft
  - Down draft
  - Cross draft
- Fluidized bed
  - Bubbling fluidized bed
  - Circulating fluidized bed
- Entrained flow

Advantages of Fluidized Bed Gasification

- Flexibility of fuel
- Wider particle size distribution of feedstock
- Efficient HMT due to better feedstock/oxidant mixing
- Higher conversion of feedstock
- Higher efficiency (75% to over 90%)
- Avoid clinker formation

Objectives

- Develop a 3D model of biomass gasification process that incorporates energy, flow and reaction chemistry
- Find suitable kinetic parameters for the model
- Implement the model into CFD simulation package (ANSYS Fluent®)
- Investigate design aspects of the selected gasifier e.g. feed position, feed angle
- Study the effect of gasifying agent on the composition of product gas
- Analyze results and give further recommendations

Modeling Procedure

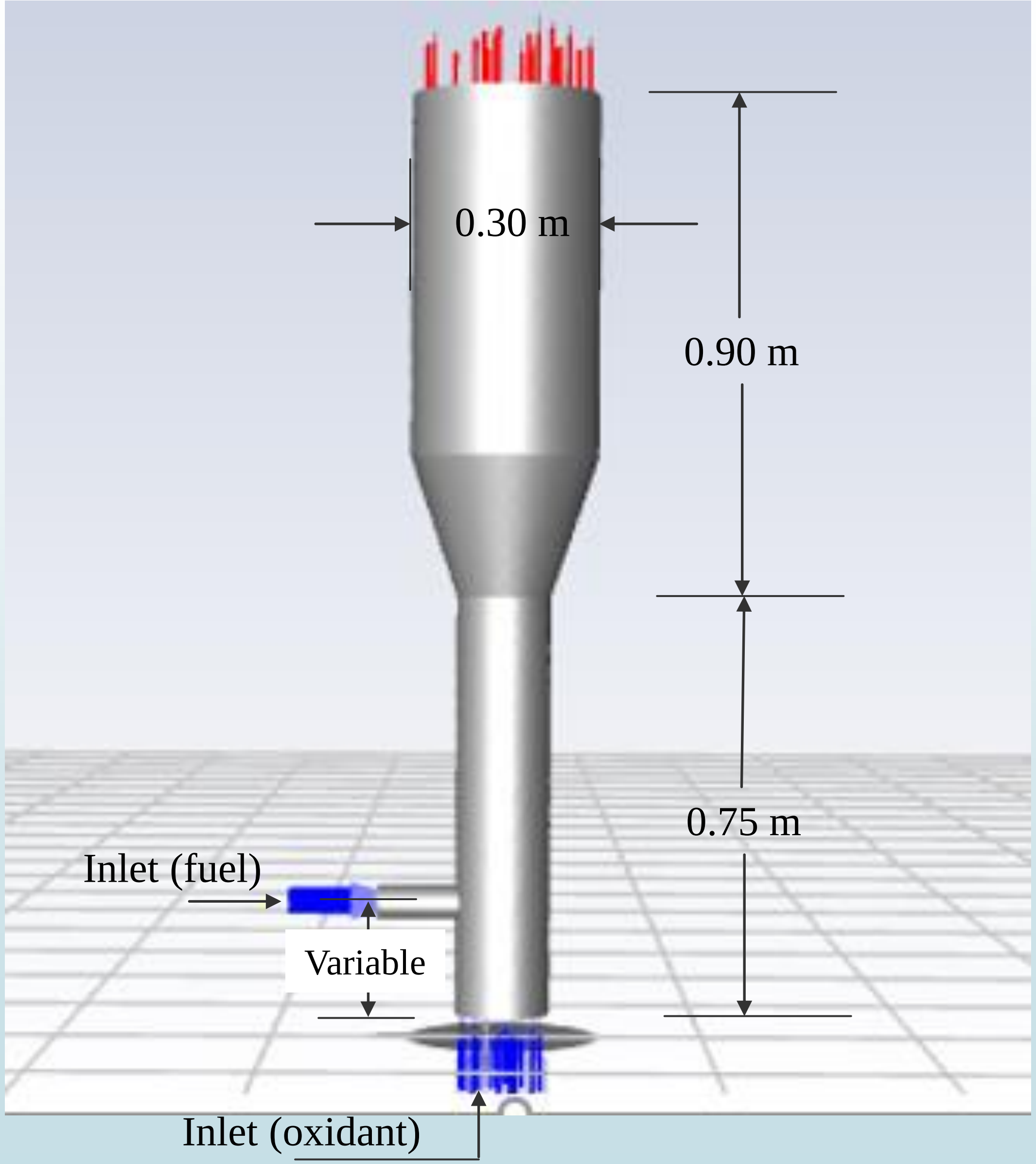
- Assumptions
- Geometry
- Domain discretization (meshing)
- Mesh independency test
- Governing Equations
- Solution procedure
- Results

Assumptions

- Steady state conditions
- Adiabatic conditions
- Fluids are treated as ideal gas
- k-epsilon turbulence model is assumed
- Inert phase is ignored
- Volatile break up approach is used
- Homogeneous reaction kinetics assumed

Geometry [1]

Geometry model of the domain with different components and dimensions developed using ANSYS DESIGN MODELER®



Grid Independency Test

A single reaction kinetic model with simple settings is used [2]

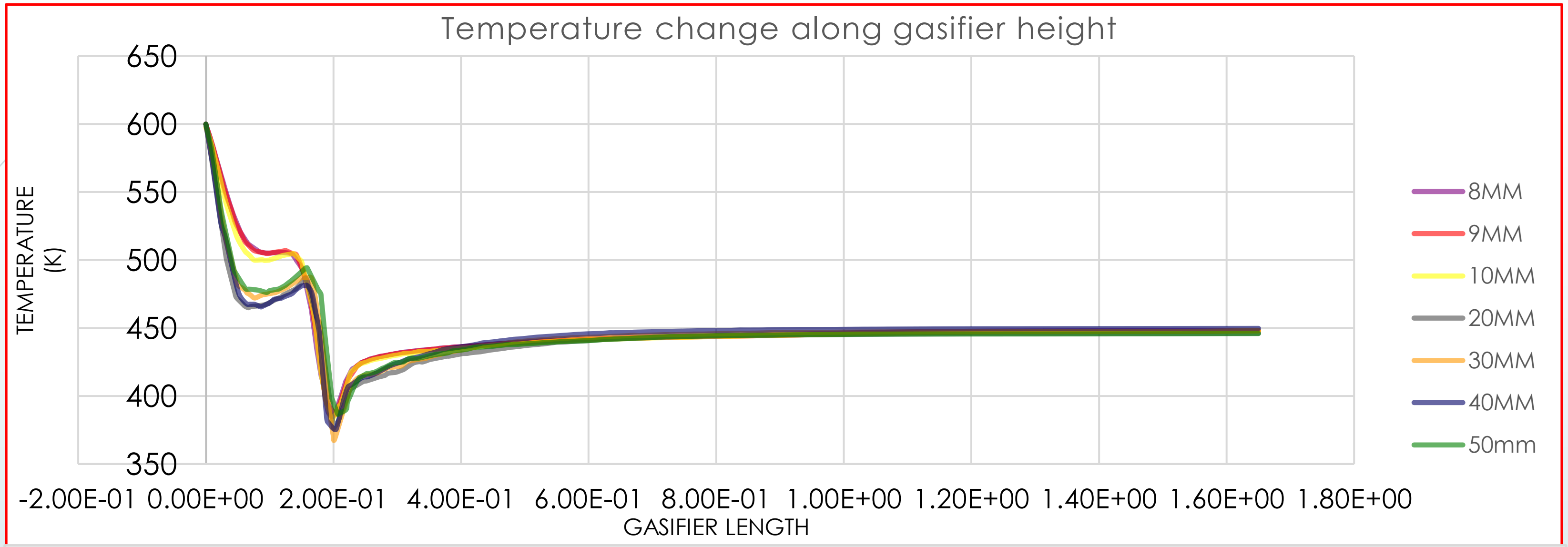
Material	Mass Flow Rate (kg/hr)	Composition (%)		Temperature (K)
Wood -Volatiles	3.65	Wood -Volatiles	100	300
Air	3.88	O_2 N_2	21 79	600

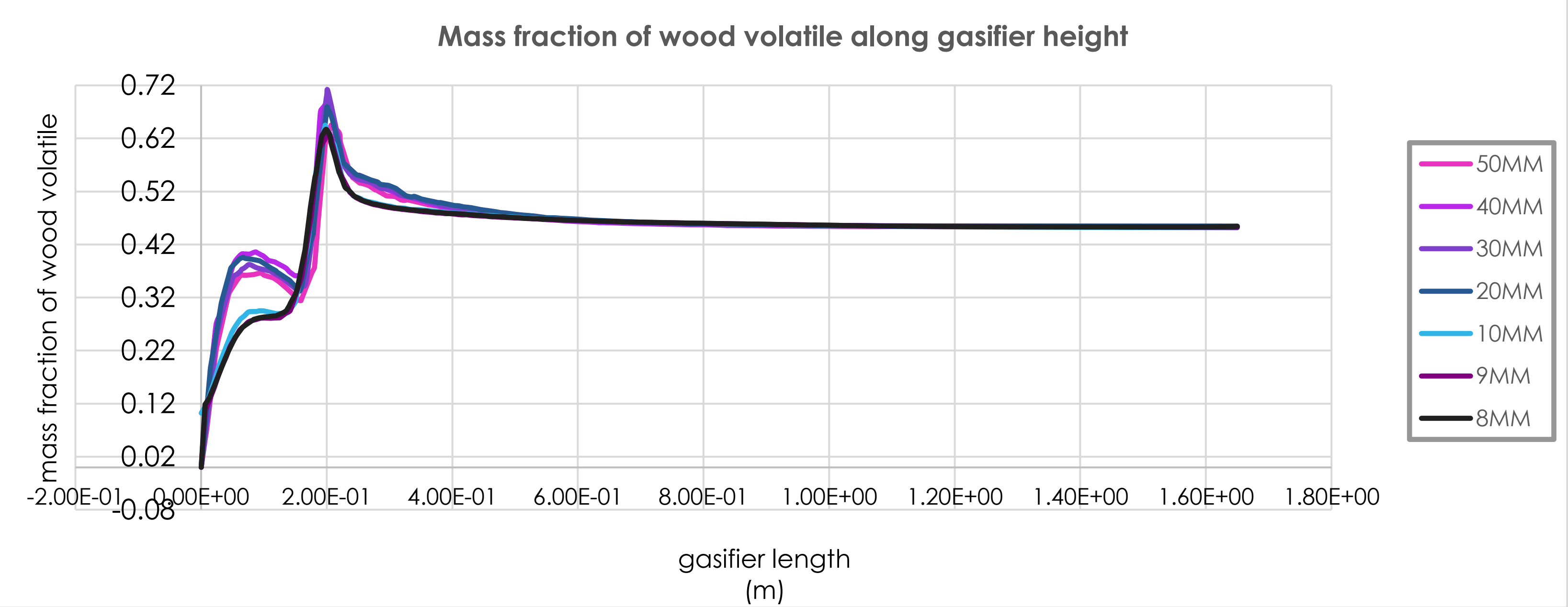
$$\text{wood-volatiles} + 1.058\ O_2 \rightarrow CO_2 + 1.1191\ H_2O$$

$$-r_A = k_o e^{-E/RT}\, c_A^a\, c_B^b$$

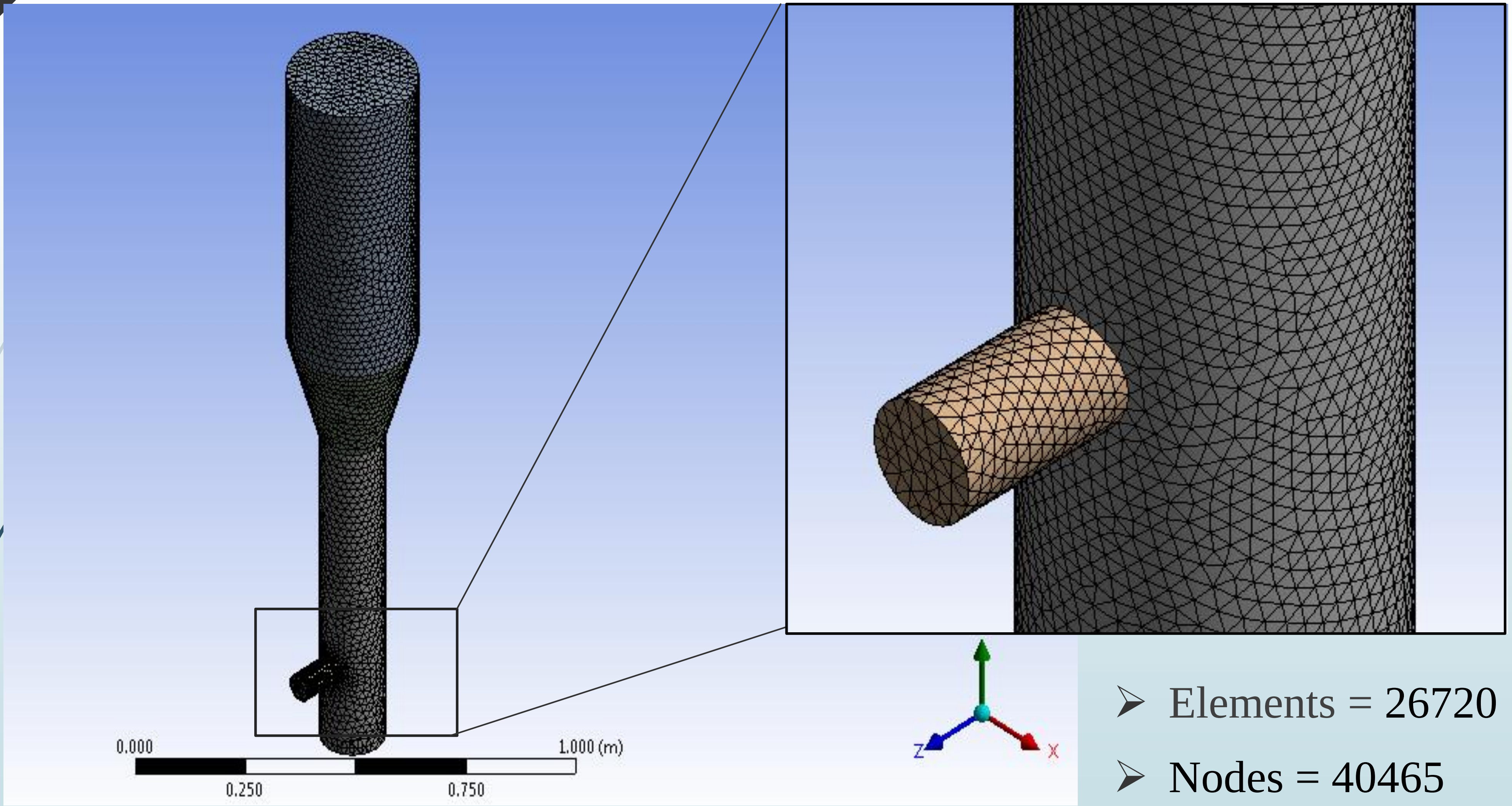
$$-r_A = 2.119\ \text{e}+11\ \left(EXP^{-2.027\ \text{e}+11/\text{RT}}\right) [\text{wood volatile}]^{0.2} [O_2]^{1.3}$$

Grid Independency Test





3D Tetrahedral Mesh



- Elements = 26720
- Nodes = 40465

Governing Equations [3]

1. Mass Balance:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

2. Momentum Balance:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i$$

3. Energy Balance:

$$\nabla . (\rho \vec{u} H) = \nabla . \left(\frac{k_t}{c_P} \nabla H\right) + S_h$$

x_i, x_j = direction vector, [-]
u_i, u_j = velocity vector, [ms^{-1}]
p = pressure, [Pa]
τ_{ij} = stress tensor, [Pa]
g_i = gravitational force, [ms^{-2}]
F_i = mass force, [N]
H = enthalpy, [Jkg^{-1}]
k_t = thermal conductivity, [$Wm^{-1}K^{-1}$]
c_P = avg. specific heat, [$Jkg^{-1}K^{-1}$]
S_h = heat source term, [Wm^{-3}]

Governing Equations (continued)

4. Species Balance:

$$\frac{\partial}{\partial x_i}\rho u_i f_1 = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_t}\frac{\partial f_1}{\partial x_j}\right) + S_i$$

5. Turbulent Kinetic Energy:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon$$

6. Dissipation Kinetic Energy:

$$\frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}(C_{1\varepsilon}G_k + C_{2\varepsilon}\rho\varepsilon)$$

$\boldsymbol{\mu_t}$ = turbulent viscosity, [Pa.s]
$\boldsymbol{\sigma_k}$ = turbulent Prandtl number for k,[-]
$\boldsymbol{k}$ = turbulence kinetic energy, [m^{2}s^{-2}]
$\boldsymbol{G_k}$ = generation of turbulence kinetic energy, [m^{2}s^{-2}]
$\boldsymbol{\varepsilon}$ **=** dissipation turbulence kinetic energy, [m^{2}s^{-3}]
$\boldsymbol{\sigma_\varepsilon}$ = turbulent Prandtl number for ε**,** [-]
$\boldsymbol{C_{1\varepsilon}}$**,** $\boldsymbol{C_{2\varepsilon}}$ = constant, [-]

Characterization of Rubber Wood [3]

Ultimate analysis (wt% dry basis)		Proximate analysis (wt % dry basis)	
C	48.27	Char	18
O	45.20	Ash	0.8
H	6.36	Volatile	81
N	0.14	Moisture content (wt % wet basis)	18.5
S	0.00	Higher heating value (kJ/kg)	20540

Volatile Break-up Approach

- Volatiles, char and ash compositions released from the rubber wood decomposition are expressed by the following general reactions.

$$\text{Rubber wood} \rightarrow \text{Volatile} + \text{char} + \text{tar} + \text{ash}$$

$$\text{Volatile} \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4CH_4 + x_5H_2O$$

Where x_i is the number of species moles ($\sum x_i = 1$)

- Volatile from the rubber wood consisting of Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) and Sulphur (S)
- Initially converted to a pseudo gas phase species, referred to as volatile

Kinetic Model

Reactions	Pre-exponential Factor (k_o)	Activation Energy (E) ($Jkmol^{-1}$)	Temperature (Exponent)	Reference
$C + H_20 \rightarrow CO + H_2$	8.268	1.75 e +8	1	[4]
$C + CO_2 \rightarrow 2CO$	8.268	1.75e+8	1	[5]
$2C + O_2 \rightarrow 2CO$	147000	1.113 e +8	1	[4]
$CO + 0.5O_2 \rightarrow CO_2$	1e+15	1.33 e+8	0	[4]
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	3.552 e+14	1.305 e+8	0	[5]
$2H_2 + 0.5O_2 \rightarrow 2H_2O$	5.159 e+15	2.8519 e+7	0	[5]
$CH_4 + H_2O \rightarrow CO + 3H_2$	3.18 e+8	1.25 e+8	0	[5]
$C + 2 H_2 \rightarrow CH_4$	8.889 e-6	6.7 e+7	1	[4]
$CO + H_20 \rightarrow CO_2 + H_2$	2.34 e+10	2.83 e+08	0	[6]
$CO_2 + H_2 \rightarrow CO + H_2O$	1.894 e+7	2.184 e+8	0	[6]

Boundary Conditions [3]

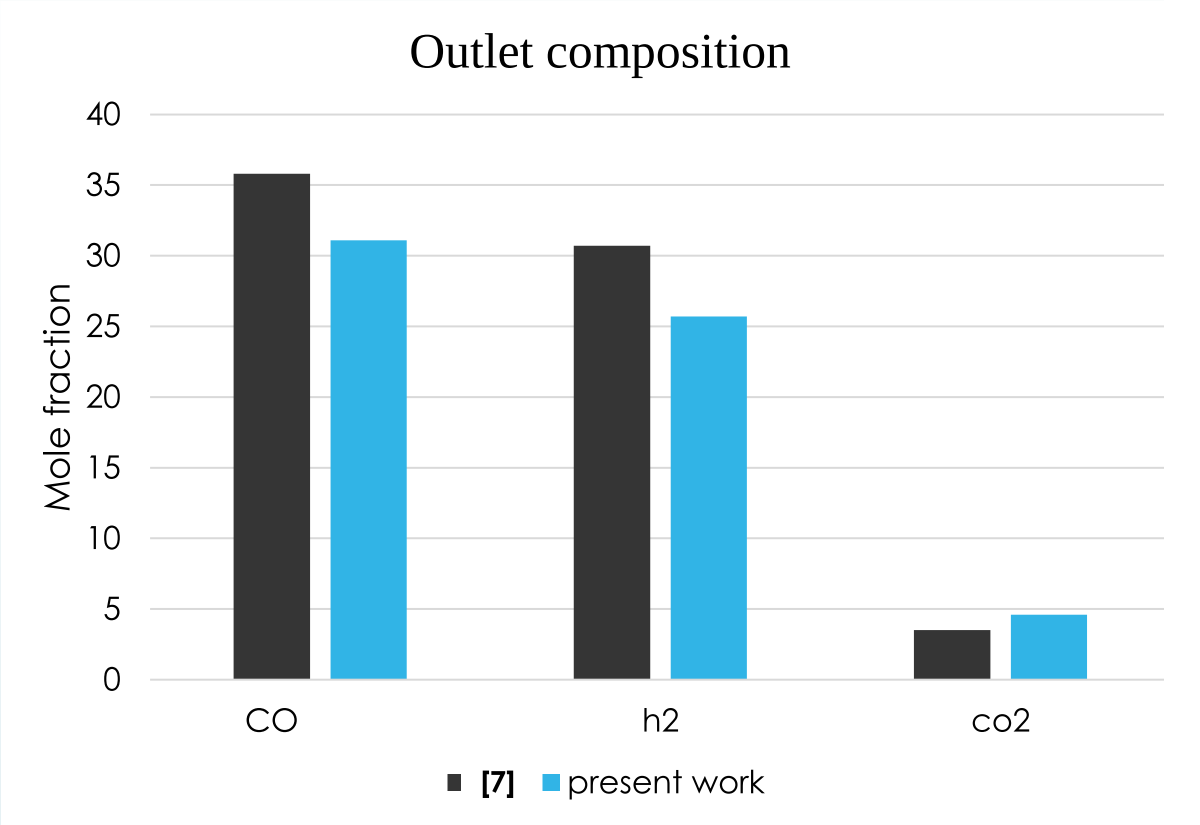
	Material	Mass Flow Rate (kg/hr)	Composition (%)		Temperature (K)
Fuel inlet	Rubber Wood	3.65	Carbon	48.27	300
			Oxygen	45.2	
			Hydrogen	6.36	
			Nitrogen	0.14	
Air inlet	Air	3.88	Oxygen	21	600
			Nitrogen	79	

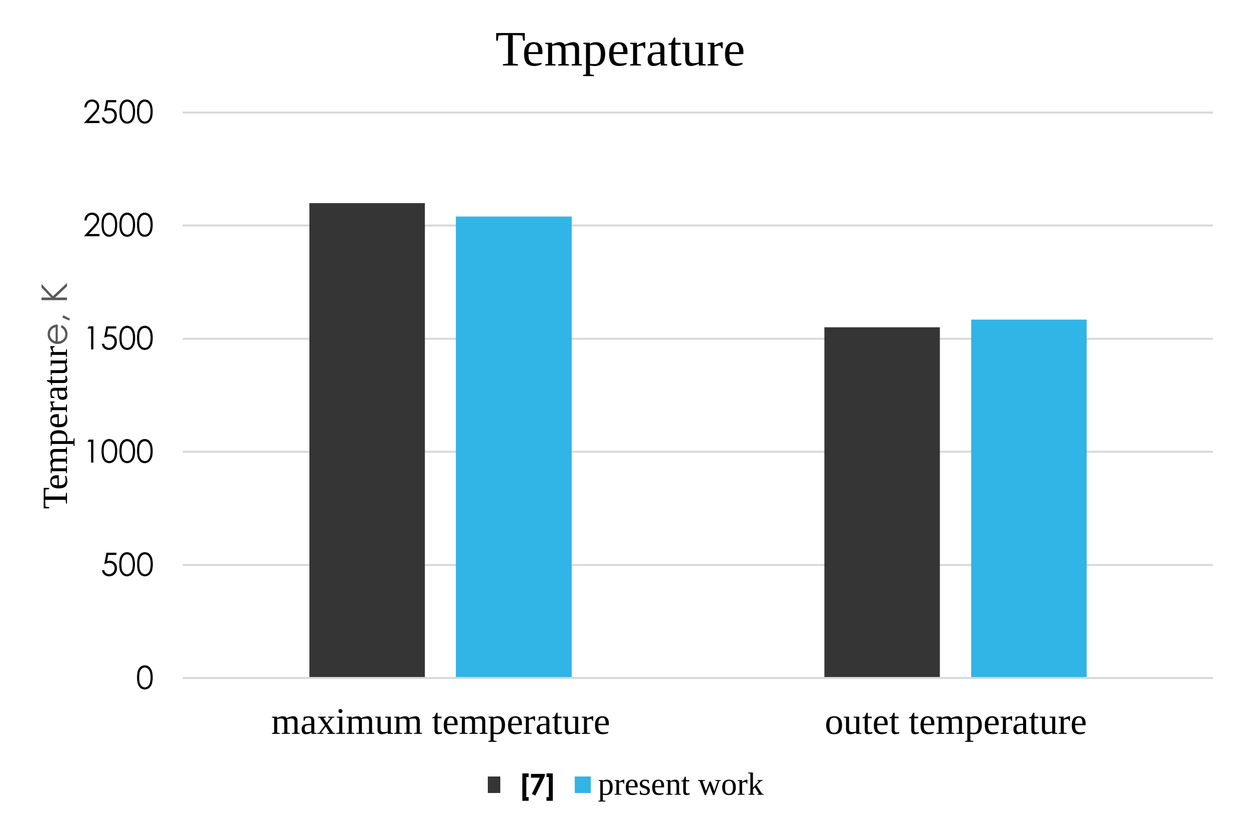
Simulation Setup

Solver	Pressure-based
Models	K-epsilon, Energy, Species Transport (Volumetric reactions,)eddy dissipation concept
Materials	Rubber Wood (Mixture of carbon, hydrogen, oxygen, nitrogen)
Boundary Conditions	Air composition: (0.21 O_2,0.79 N_2) Mass flow rate = 3.88 kg/h Rubber wood composition (0.4827 C, 0.452 O_2, 0.0636 H_2 ,0.0014 N_2) Mass flow rate = 3.65kg/h
Pressure Velocity Coupling	Phase-Coupled

Results

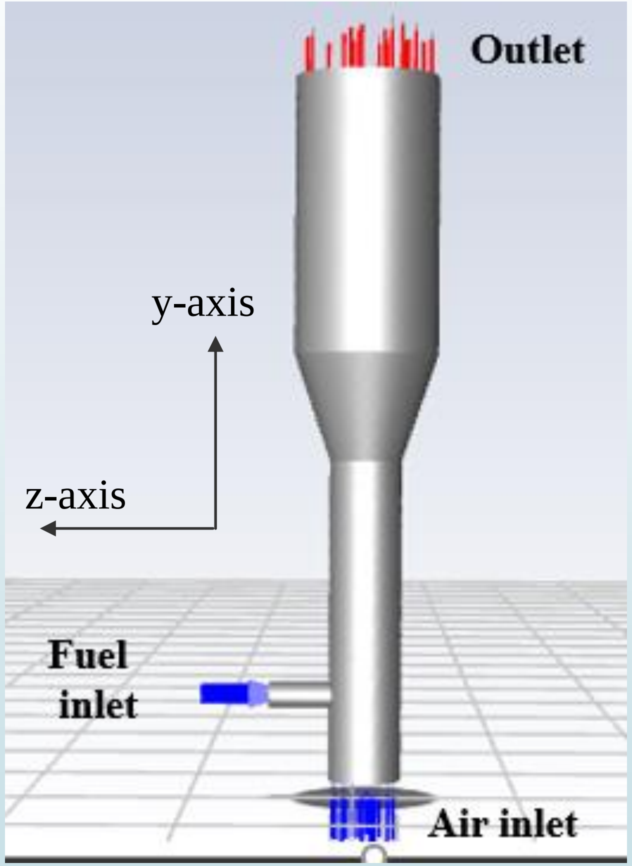
Model Comparison



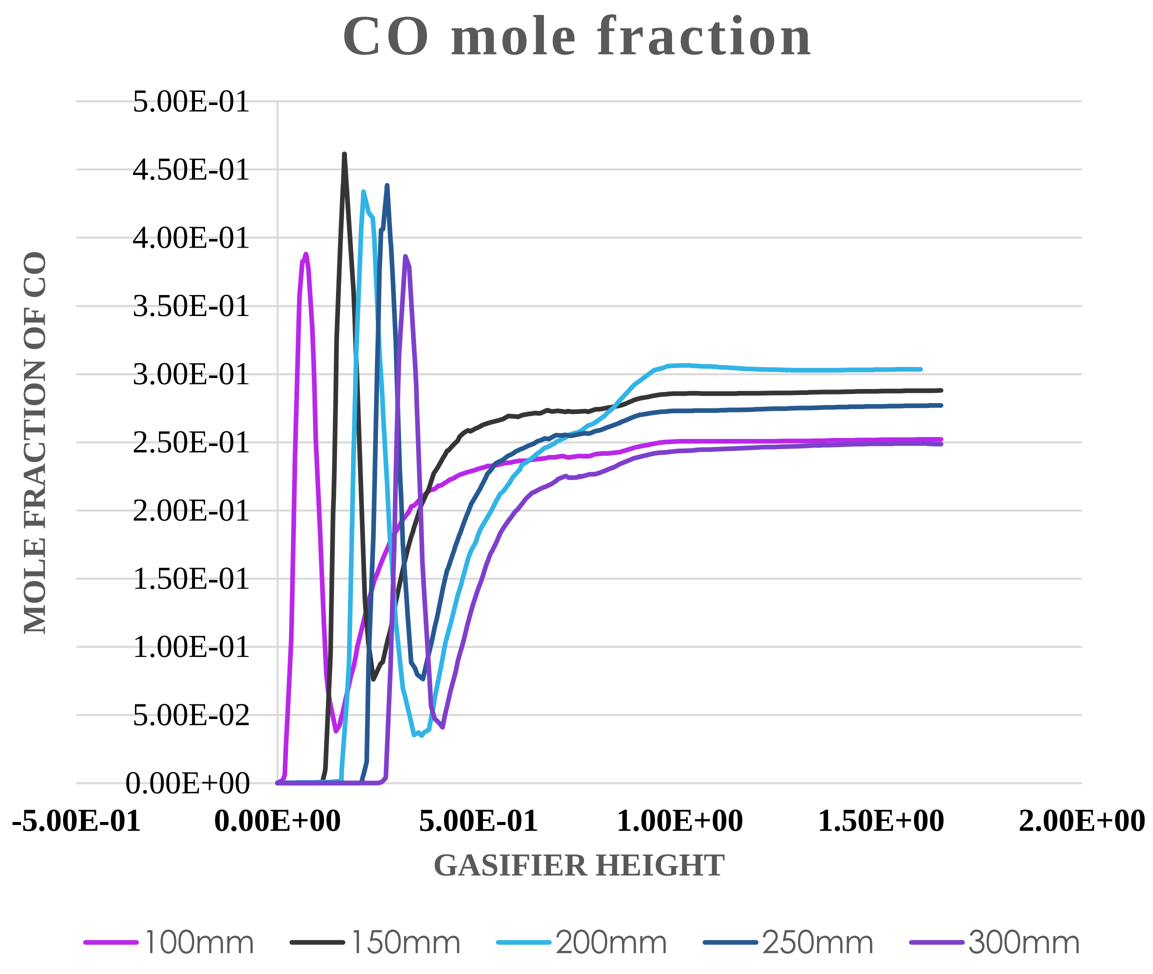


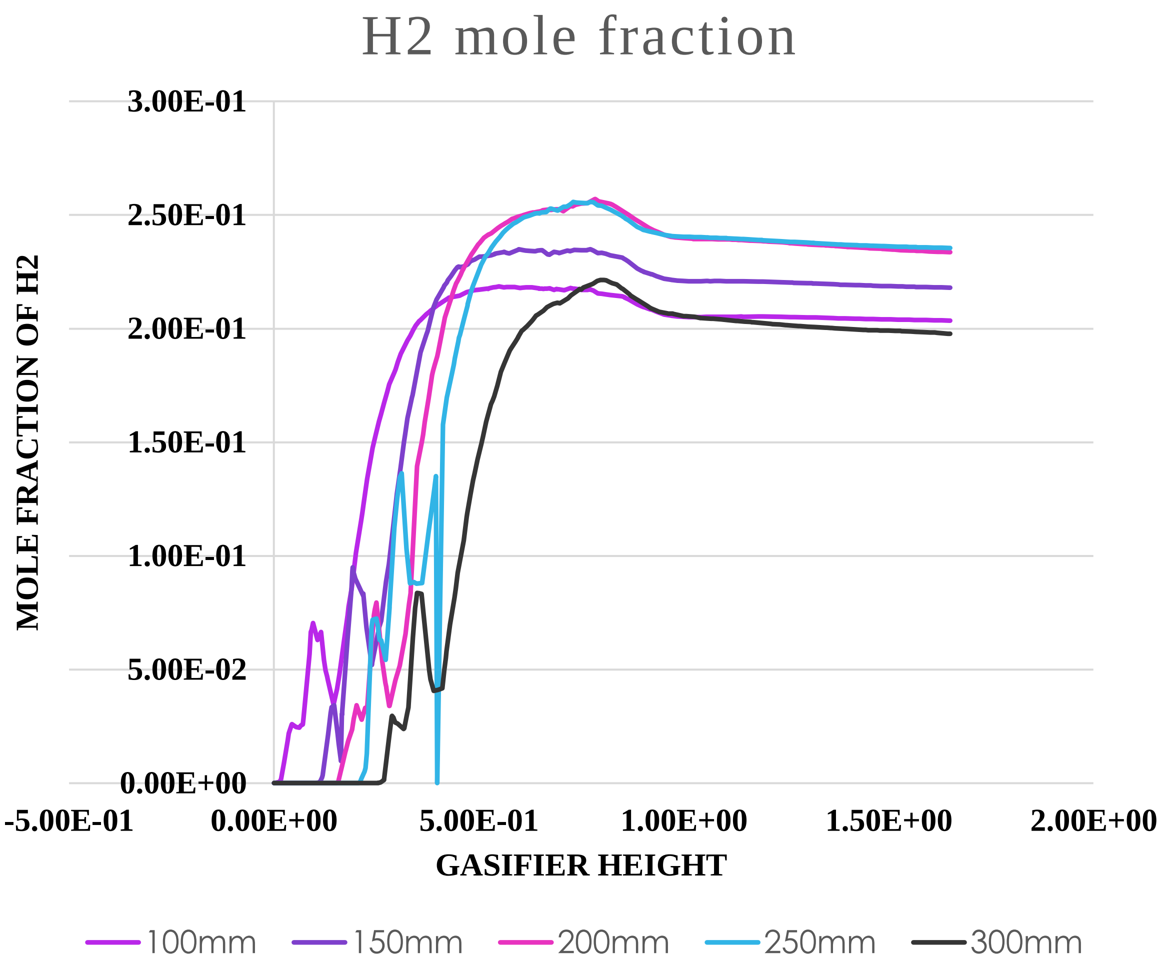
Effect of Vertical Position & Angle of Fuel inlet

- Vertical position of fuel inlet is varied as follows:
  1. 100mm
  2. 150mm
  3. 200mm
  4. 250mm
  5. 300mm
- Feed angle of fuel inlet w.r.t. z-axis is varied as follows:
  1. 0^o
  2. 30^o
  3. 60^o



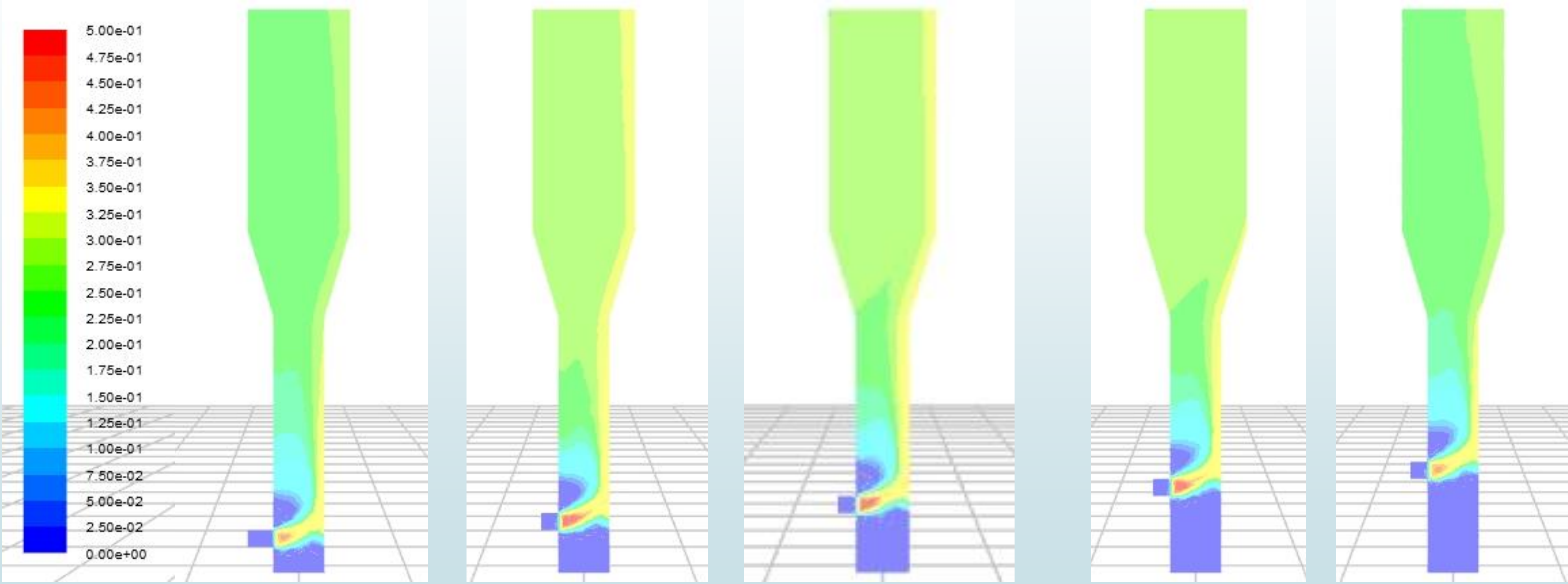
Vertical Feed Position ➔ Mole Fraction of CO and H_2





Vertical Feed Position ➔ Mole Fraction of CO

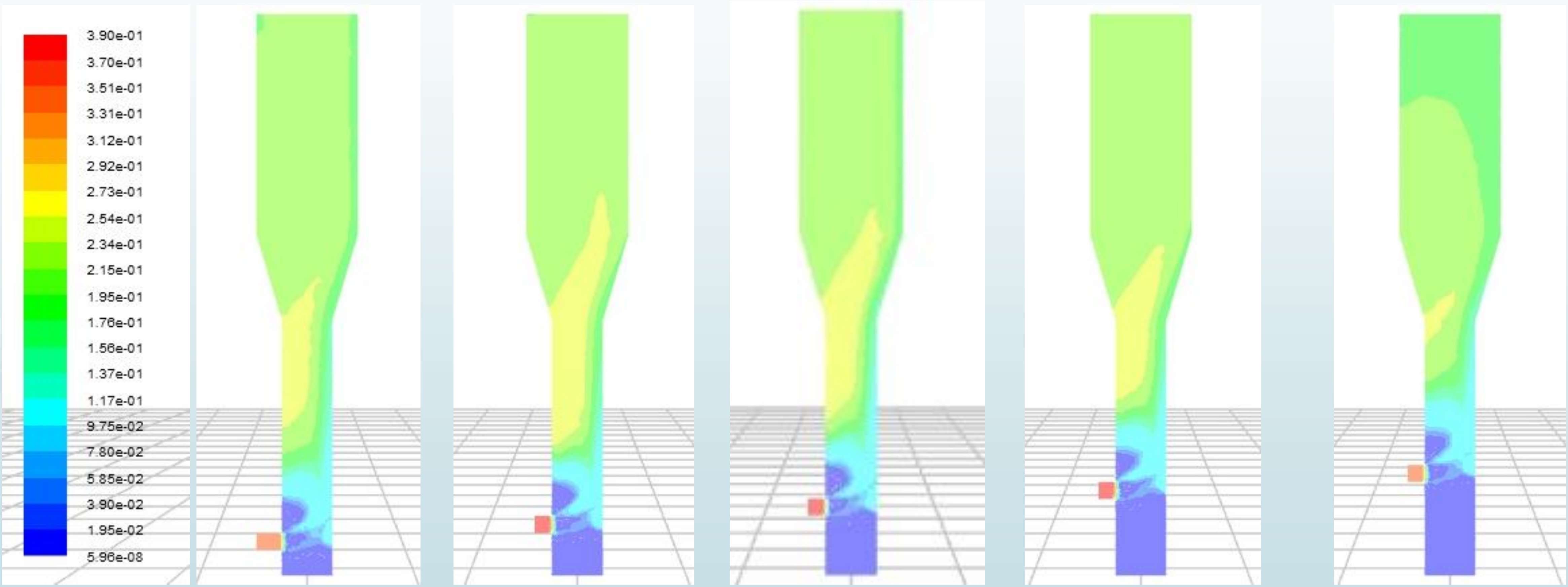
Contours of CO mole fraction



Position 100mm 150mm 200mm 250mm 300mm

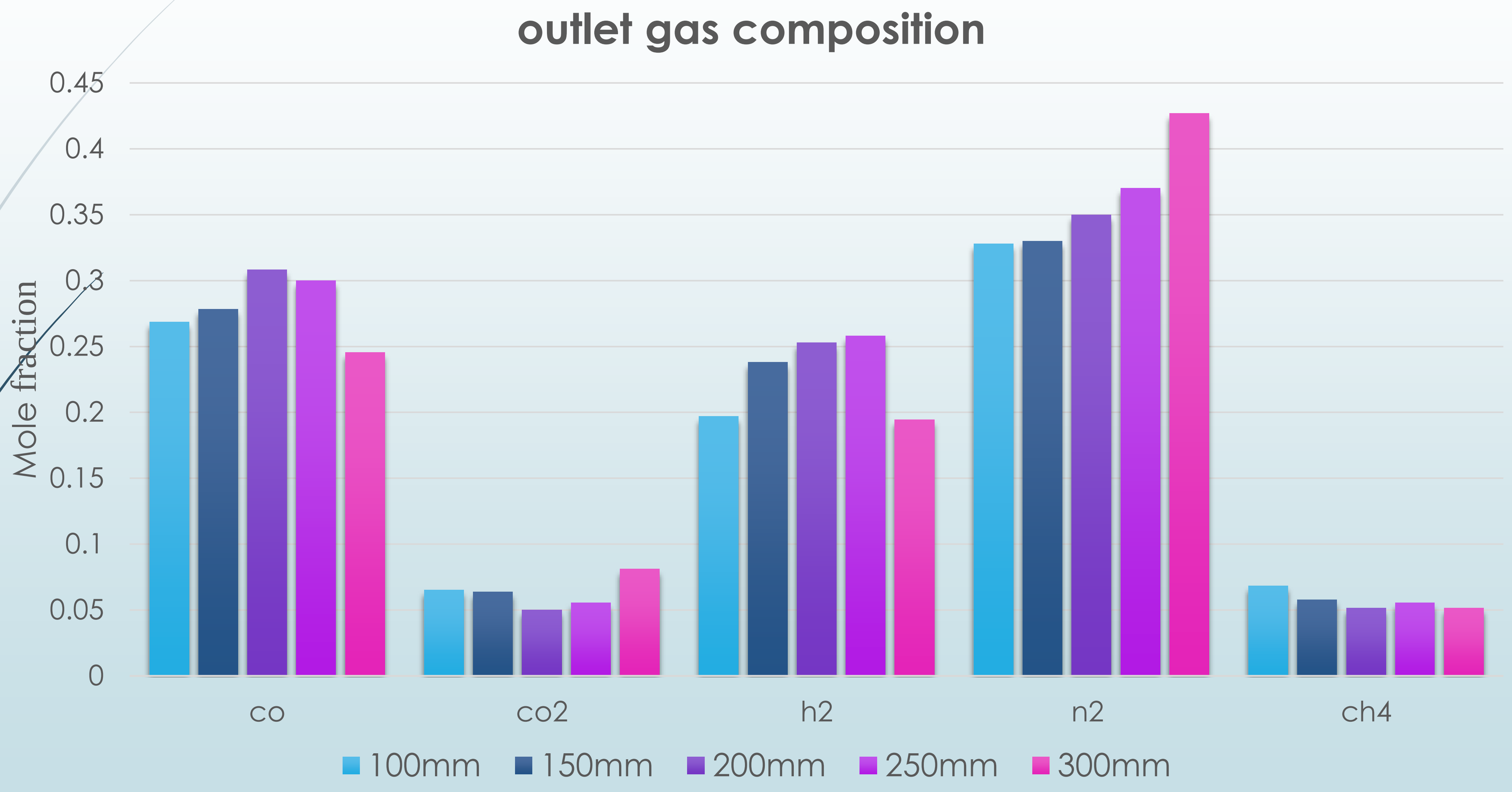
Vertical Feed Position → Mole Fraction of H_2

Contours of H_2 mole fraction

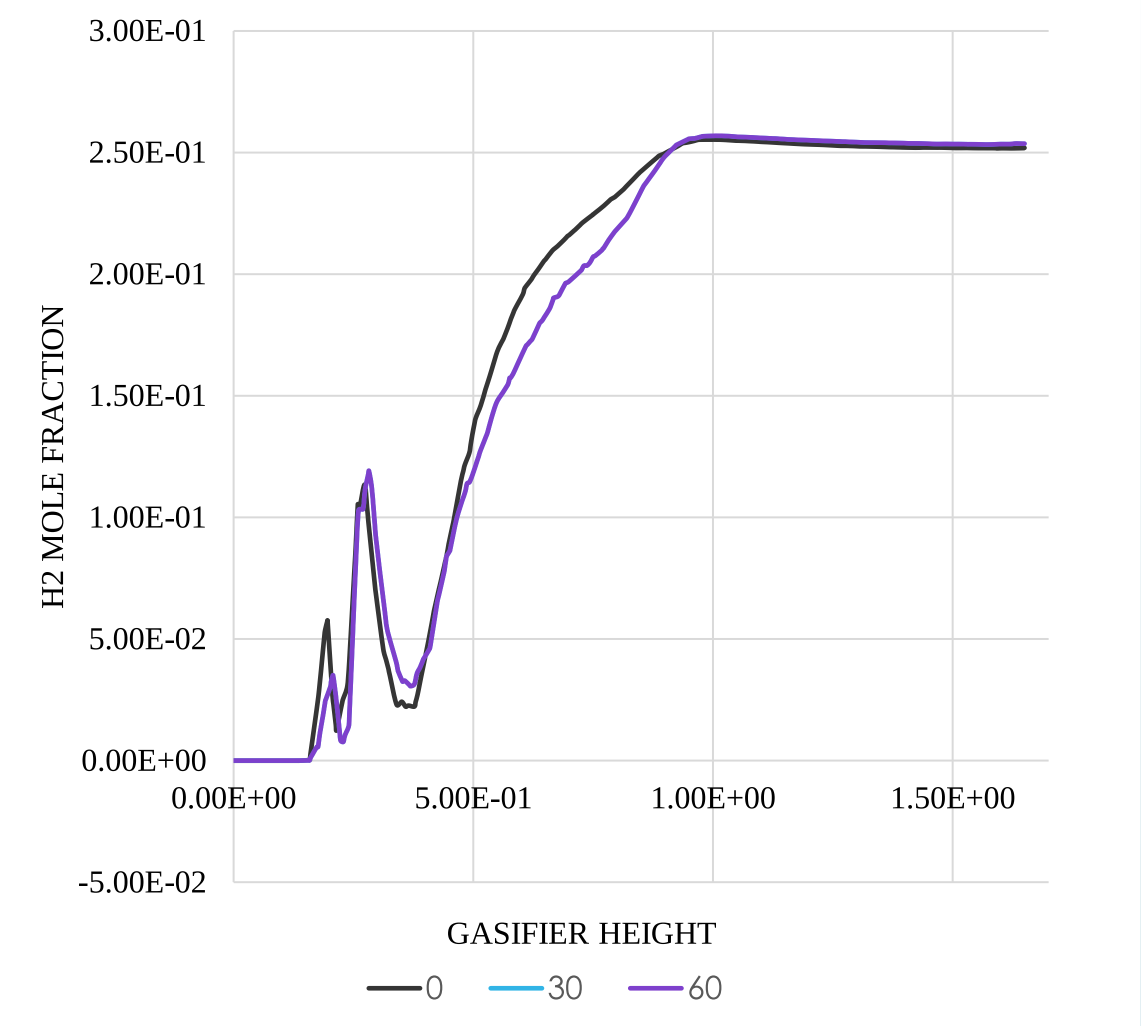


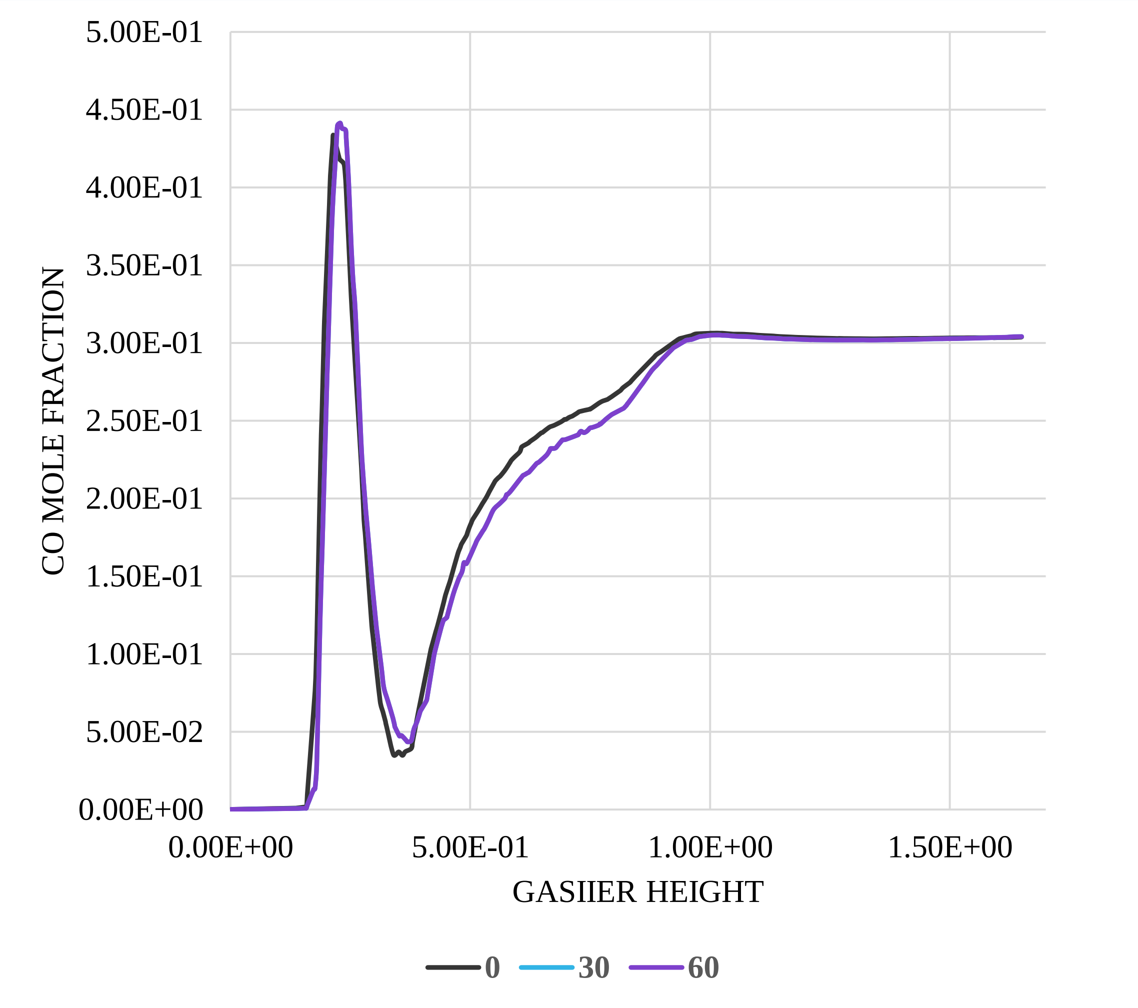
Position	100mm	150mm	200mm	250mm	300mm

Vertical Feed Position ➔ Product Gas Composition



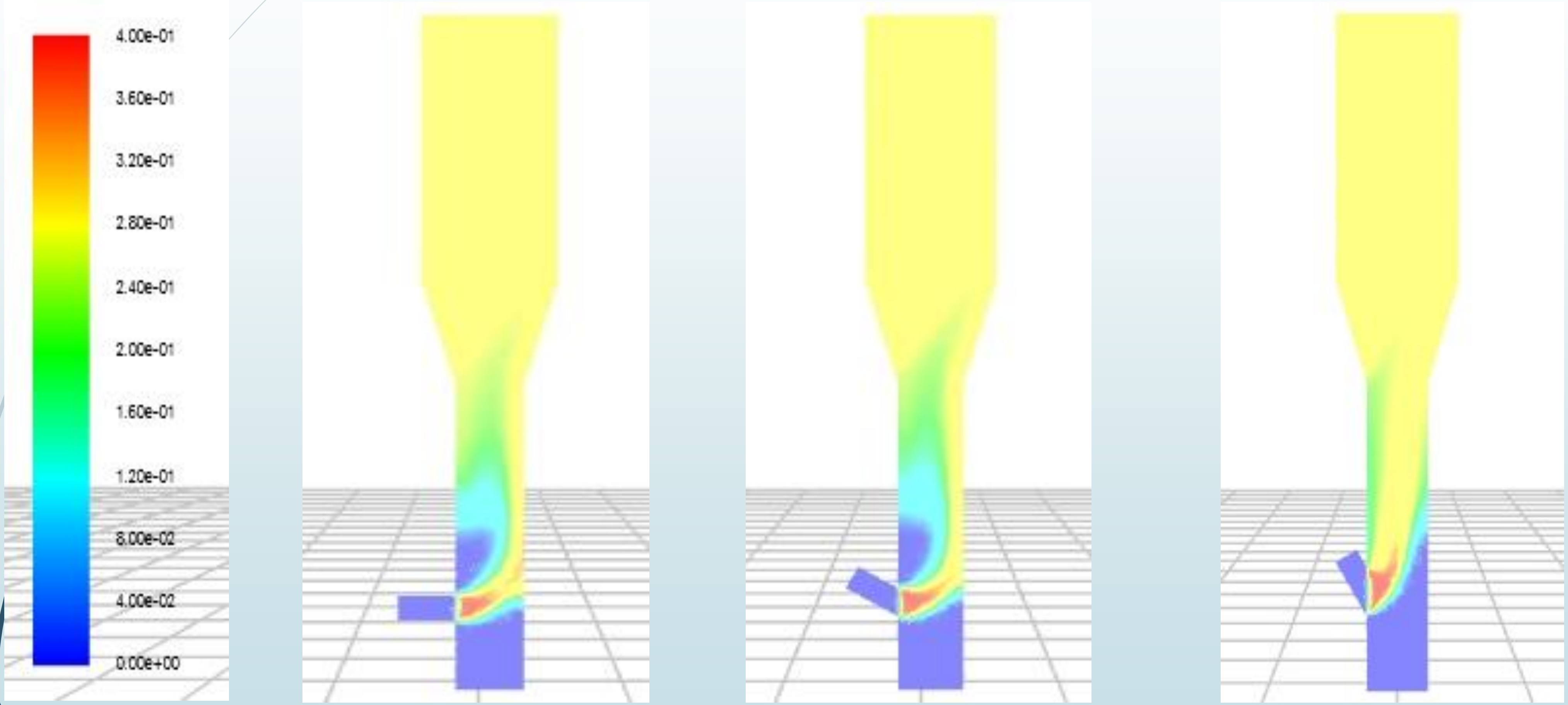
Feed Angle ➔ Mole Fraction of CO and H_2





Feed Angle ➔ Mole Fraction of CO

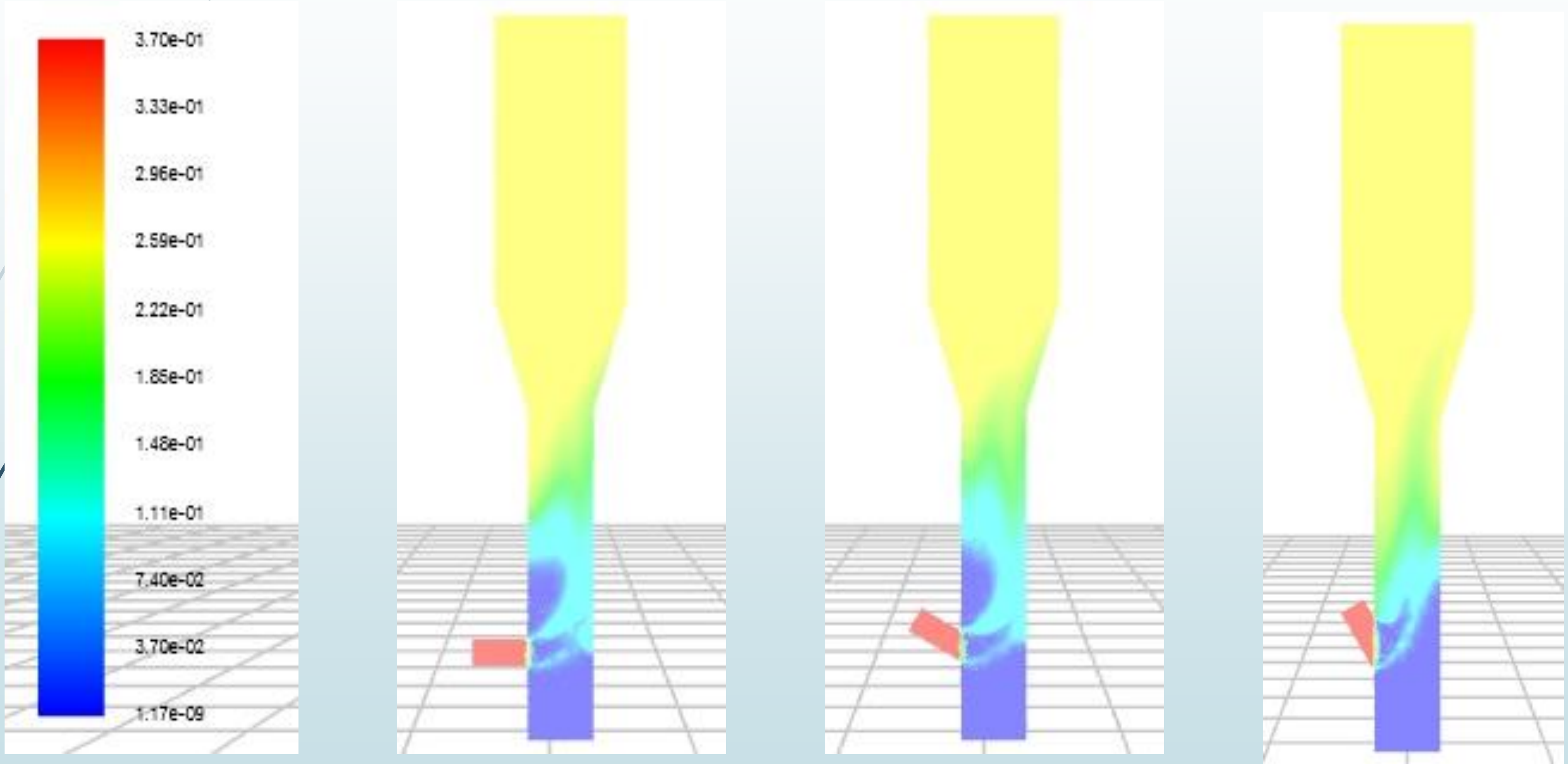
Contours of CO mole fraction



Feed angle ➔ 0 30 60

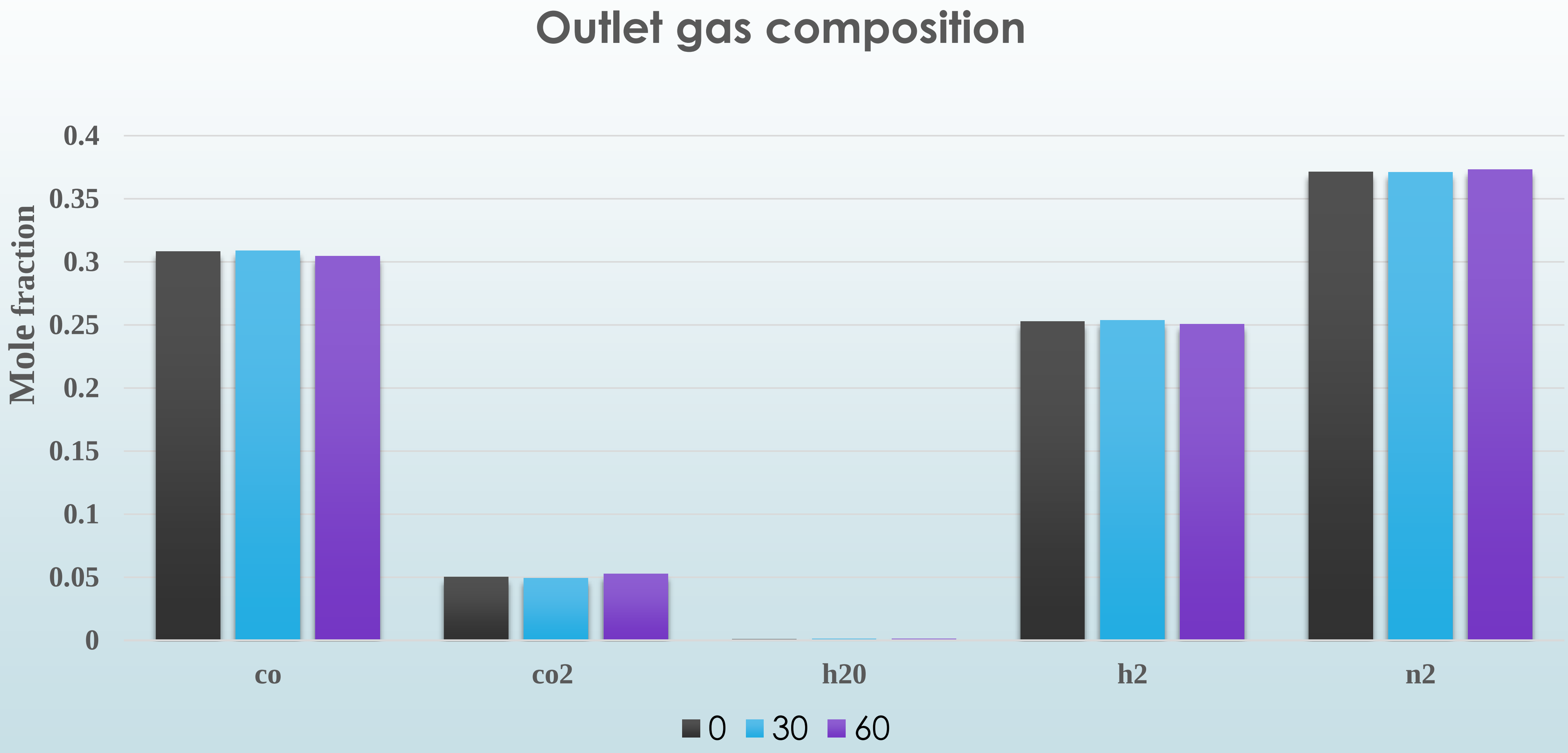
Feed Angle ➔ Mole Fraction of H_2

Contours of H_2 mole fraction



Angles ➔ 0 30 60

Feed Angle → Product Gas Composition

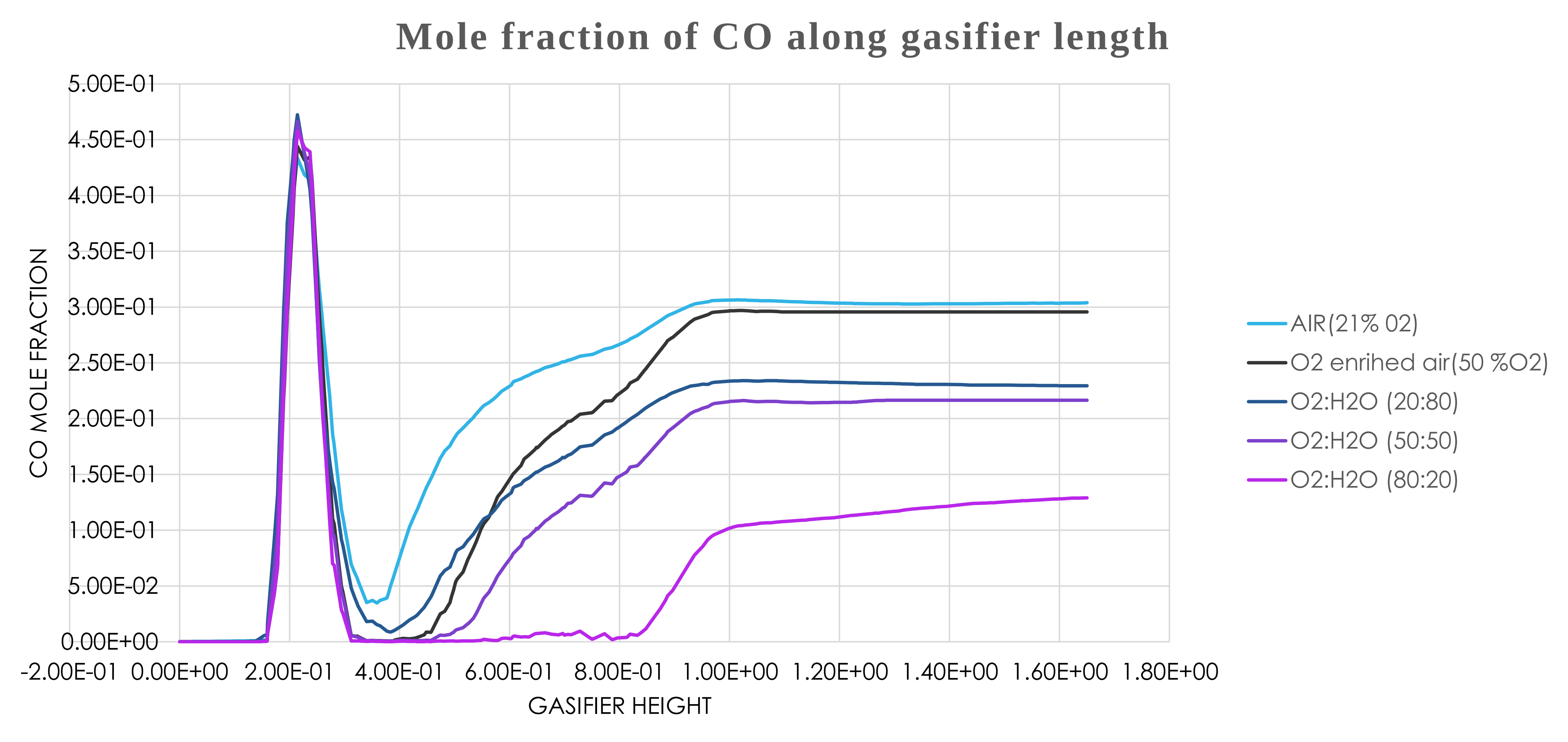


Effect of Gasifying Agent

Following compositions of different gasifying agents are simulated

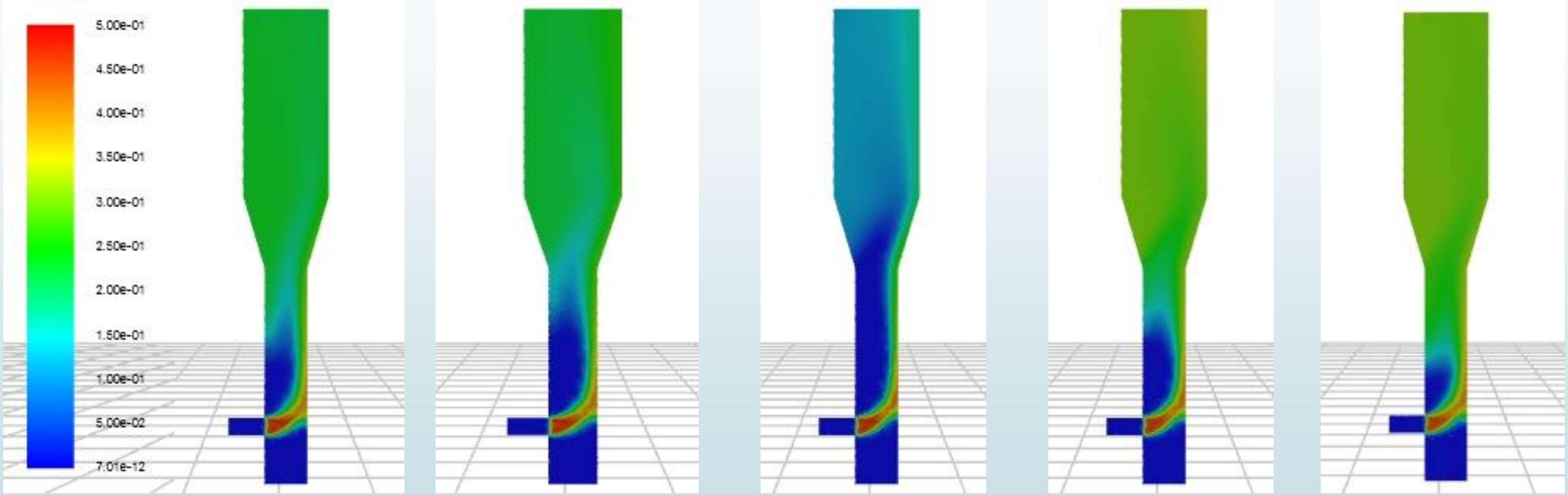
1. 0.2% O_2 : 0.8% H_20
2. 0.5% O_2 : 0.5% H_20
3. 0.8% O_2 : 0.2% H_20
4. Oxygen Enriched Air (0.5% O_2)
5. Air (0.21% O_2)

Gasifying Agent → Mole Fraction of CO



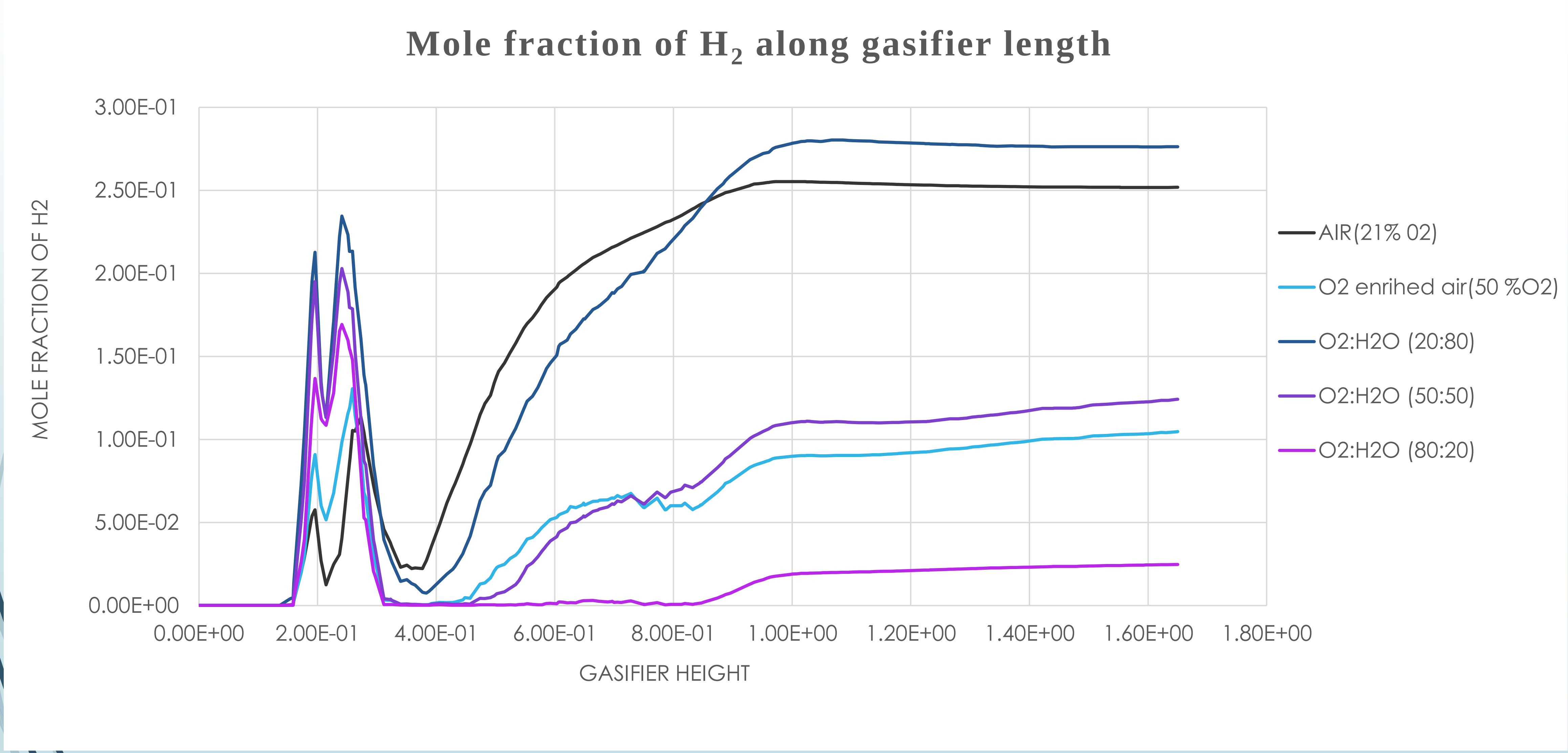
Gasifying Agent ➔ Mole Fraction of CO

Contours of CO mole fraction



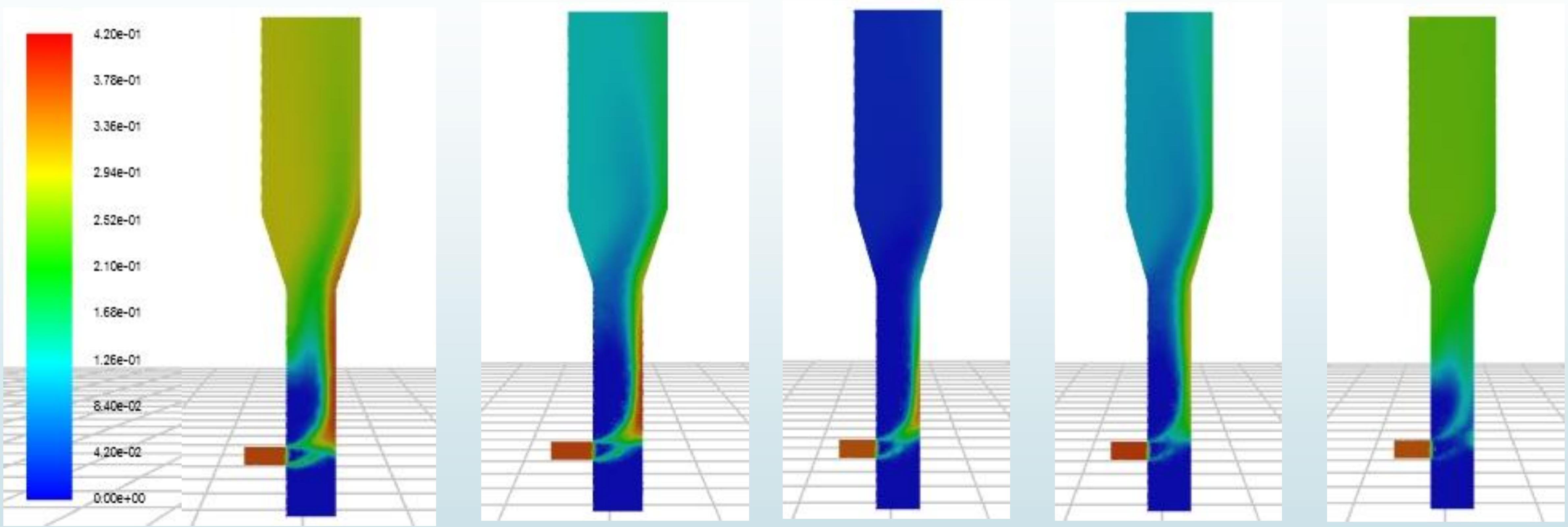
0.2% O2 : 0.8% H20 | 0.5% O2 : 0.5% H20 | 0.8% O2 : 0.2% H20 | Oxygen Enriched Air (0.5% O2) | Air (0.21% O2)

Gasifying Agent → Mole Fraction of H_2



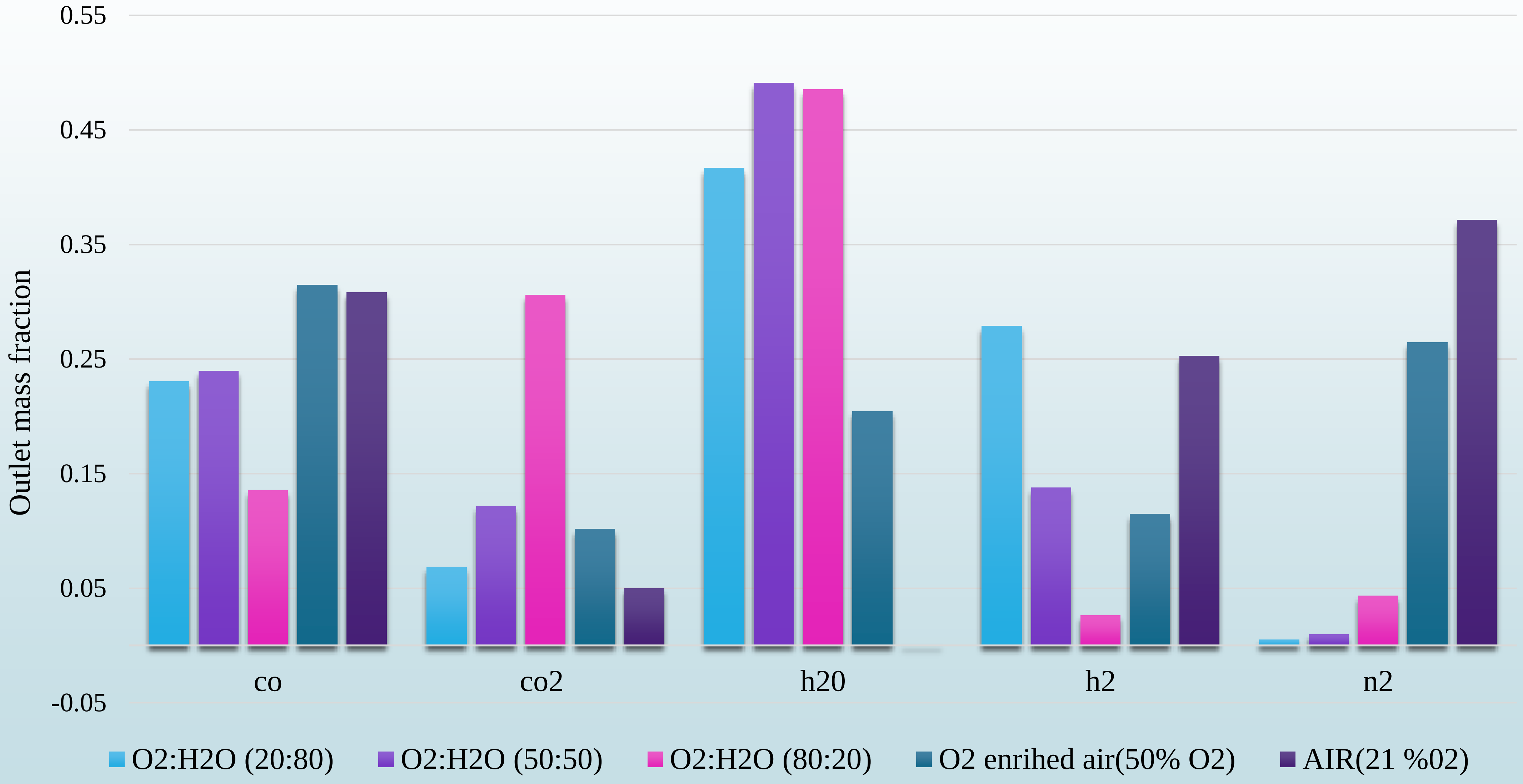
Gasifying Agent ➔ Mole Fraction of H_2

Contours of H_2 mole fraction



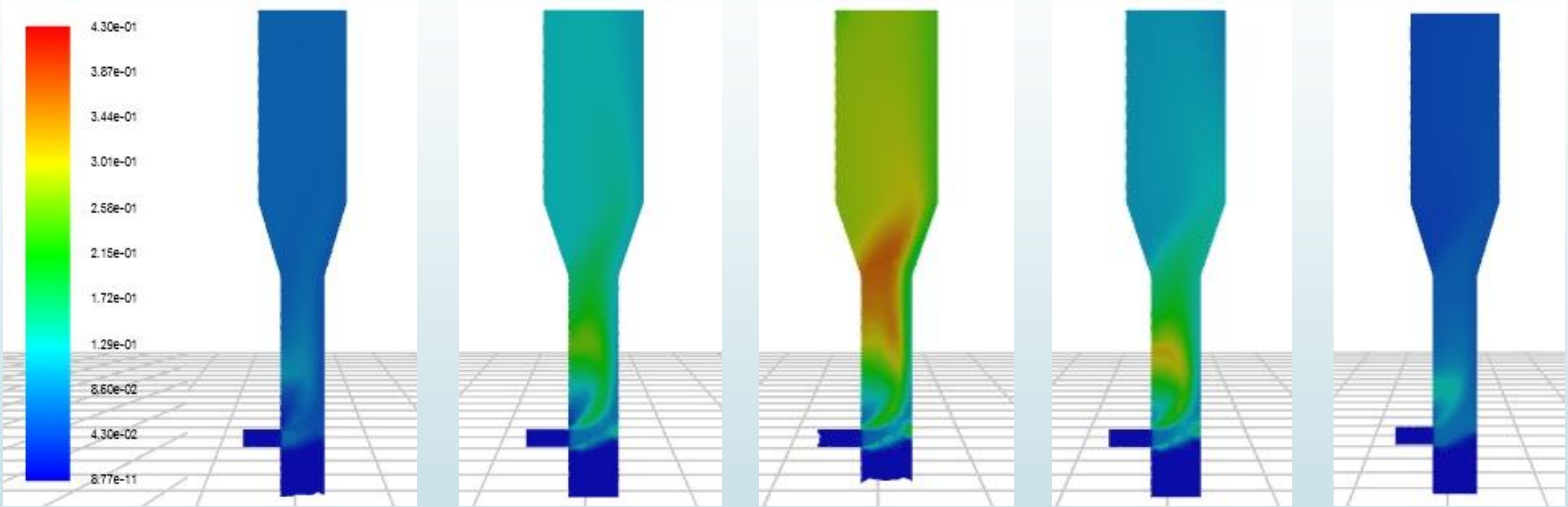
0.2 O2 : 0.8 H20 | **0.5 O2 : 0.5 H20** | **0.8 O2 : 0.2 H20** | **O_2 Enriched Air (0.5 O_2)** | **Air (0.21% O2)**

Gasifying Agent ➔ Product Gas Composition



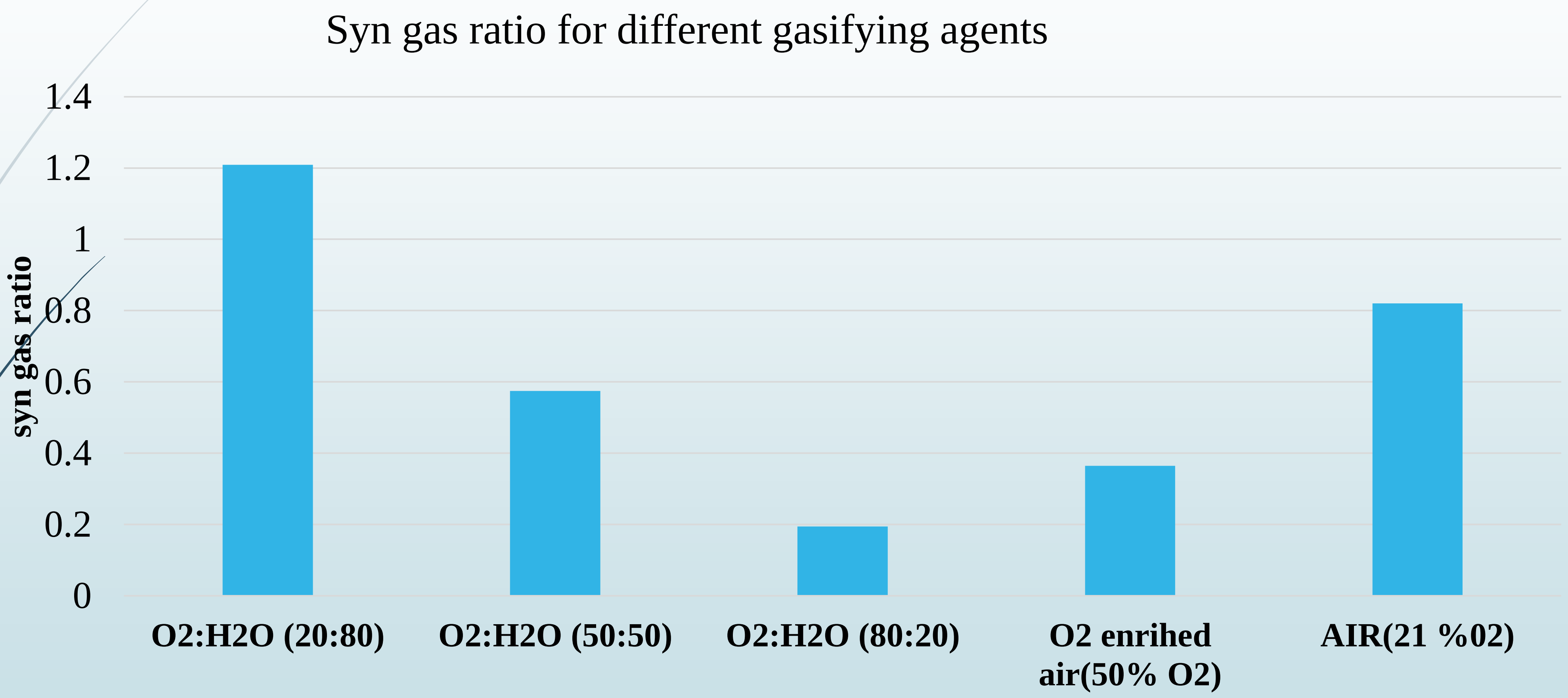
Gasifying Agent ➔ Mole Fraction of CO_2

Contours of CO_2 mole fraction



0.2 O2 : 0.8 H20 | **0.5 O2 : 0.5 H20** | **0.8 O2 : 0.2 H20** | **O_2 Enriched Air (0.5 O_2)** | **Air (0.21% O2)**

Gasifying Agent ➔ Syn Gas Ratio (H_2:CO)



Conclusion

- Vertical positions of feed inlet at 200 mm and 250 mm gives rise to better quality syn gas in terms of CO and H_2 fraction
- Feed angle is found to have negligible impact on outlet gas composition.
- Increasing O2 in gasifying agent, CO2 in product stream increases thereby decreasing CO.
- Increasing O2 also increases water content in product gas that negatively impacts the quality of syngas
- Gasifying agent comprising a mixture of 20% Oxygen and 80% steam gives rise to highest syn gas ratio compared to the rest

Outlook

- To incorporate heterogeneous reaction kinetics in the model
- To include inert (solid) phase in the model
- To further improve and refine the mesh

Recommendations:

Results obtained gave a good insight into the fluidized bed gasification process. The model can serve as a basis to further investigate different aspects of the fluidized bed gasification process.

THANK YOU

References

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