

NUMERICAL INSIGHTS INTO GAS MIXING SYSTEM DESIGN FOR ENERGY CONVERSION PROCESSES

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Uniform gas mixing is important in various scientific and engineering domains, particularly in a chemical reactor design employing pre-mixed gases for processes. Assessing the performance of different mixer designs through physical prototypes can be resource-intensive and time-consuming. Consequently, this study underscores the significance of numerical simulations to optimize gas mixing and distribution systems in energy conversion applications.

The research primarily focuses on varying the base mixer geometry by modifying the configuration of cross-flow inlets alongside the chambers. By employing numerical simulations, critical factors influencing mixing uniformity are identified, and innovative solutions are proposed to enhance system performance. Additionally, this work extends its application to improving the operational conditions of an industrial biomass gasifier, underlining the practicality of numerical modelling in addressing complex engineering challenges.

Keywords: *Computational fluid dynamics, gas mixing, partial oxidation, syngas production.*

1. INTRODUCTION

Gas mixing devices play a crucial role in various chemical reactor designs, particularly in the production of synthesis gas, which finds applications in hydrogen production, methanol and DME synthesis, and synthetic fuel production [1]. Synthesis gas

production methods often involve partial oxidation (POX) of natural gas or hydrocarbon feedstocks [2] [3], which can be either non-catalytic or catalytic, including auto-thermal reforming (ATR).

While biomass gasification and POX

differ in many aspects, they share common requirements for oxidizer input and gas mixing. The issue of slag formation in gasification, caused by ash deposits on gasifier walls, poses challenges to equipment production [4]. Despite its significance, the phenomenon of slagging remains insufficiently explored, especially concerning its link to the gas flow behaviour. Most modelling attempts look at one or two-dimensional models [5], thus not taking into consideration important spatial behaviour of the slagging process.

In all of these syngas production types, the mixing device is an important part of the equipment, regardless of what type of process is implemented in a particular case, catalytic or in free volume, and in what ratio the initial components react. Its development is always accompanied by special studies [6], and the results are protected by copyright.

In POX processes, the risk of free carbon formation is associated with localized changes in reactant concentrations, especially when it comes to the partial oxidation of natural gas, rather than pure methane. C₂+ hydrocarbons contained in natural gas are more likely to produce soot than pure methane [7]. Another problem is that in order to achieve an optimal ratio of H₂:CO:CO₂ in the resulting mixture used for further processing (e.g. methanol synthesis), the original mixture must have a small oxidant:fuel ratio [8]. In this case, the mixture becomes difficult to ignite, and the presence of local irregularities in the composition as a result of poor mixing can lead to zones where reactions do not occur.

Catalytic POX of natural gas also requires uniform mixing of feedstocks. This is due to the fact that, in contrast to non-catalytic oxidation and ATR conversion, after mixing, the gas does not ignite, but enters the catalyst, where oxidative conver-

sion occurs. In the case of inhomogeneous mixing, spontaneous ignition may occur [9]. The probability of this increases due to the high temperatures of the source gases. Spontaneous ignition after mixing can lead to soot formation and deterioration of the catalyst, on the one hand, and to a violation of the technological regime and stopping the unit, on the other. Also, homogeneous mixing leads to stable operation of the catalyst without local overheating.

Thus, the main task of the mixing device simulation is to optimize the mixing unit to produce a homogeneous flow after mixing. This raises the problem of determining the mixer optimality criterion. This raises the question of what constitutes an acceptable concentration gradient and what does not. The solution to this challenge seems to be a comparative analysis of different design options and the choice of the least concentration gradient. The technical characteristics of the mixer, such as the length of mixing tubes, their diameter, diameter and arrangement of injection holes, and other parameters, should be independent variables of this optimization task. Besides optimal mixing, it is also important that the mixing device generates hydraulic resistance that does not exceed the limits imposed by other reactor components.

The other device considered in this paper is a ring collector in biomass gasification equipment. Here we take a closer look at the impact of gas input to the gasifier and the role of asymmetry of the flow through the inlets in slag formation. This study has been done in partnership with a company that experienced problems with asymmetrical slag formation in their gasification, thus the study is done in the scope of their gasification apparatus. This puts very tight constraints on what can be changed in the existing geometry.

2. OVERVIEW OF THE GAS MIXING SYSTEMS

2.1. Chambered Gas Mixer

The gas mixer is located above the reactor and consists of several chambers. The mixing takes place in several small vertical pipes where one gas is passed at the start

of the pipe and the rest of the gases are added through small holes on the sides of the pipes.

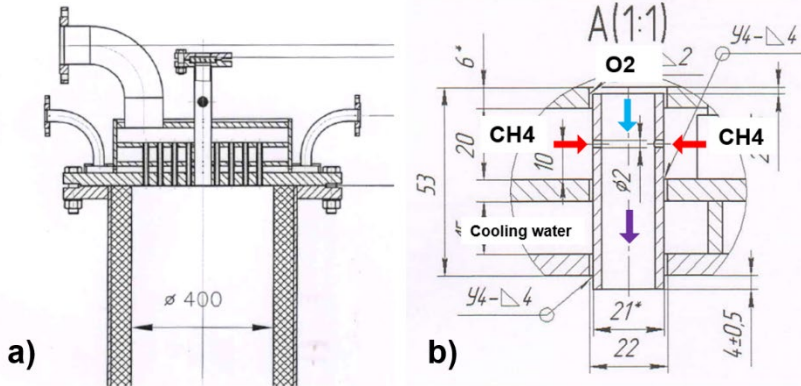


Fig. 1. Cross section of the gas mixer on top of the reactor: a) full view, b) close-up of a single pipe.

Figure 1a shows the cross section of the examined methane-oxygen mixer. Figure 1b shows an illustrative example for how a cross section of a single pipe can look like for a two-gas mixer. The two perpendicular flows create turbulence in the pipe flow that mixes both gases while they travel down the pipe. These pipes lead directly into the reactor where the mixed gases react with

each other. The mixer is intended to mix steam, oxygen and methane and distribute the mixture in the reactor. The goal of the parameter study is to maximize the uniformity of the mixed gases at the exit of the mixer. The optimizable parameters are the number of injection holes at the top and bottom chambers and the angles of the holes (more detailed description in Section 4).

2.2. Ring Collector

The gas collector is a gas injection part of an approximately eight meters high industrial entrained flow gasifier with dimensions, inlet pipe positions and inlet parameters taken from the technical specification of the gasifier. During the study, it was determined that the gas flow characteristics would be the ones that would eventually determine the presence of asymmetrical

slag. Therefore, modelling of particle-gas reactions has been neglected, deeming gas-gas reactions in the gasifier as sufficient to give a representative picture of the flow. This assumption is eventually verified by comparisons with the real-life gasifier data. Furthermore, we only consider the area around the inlets, neglecting parts above it. The geometry is given in Fig. 2.

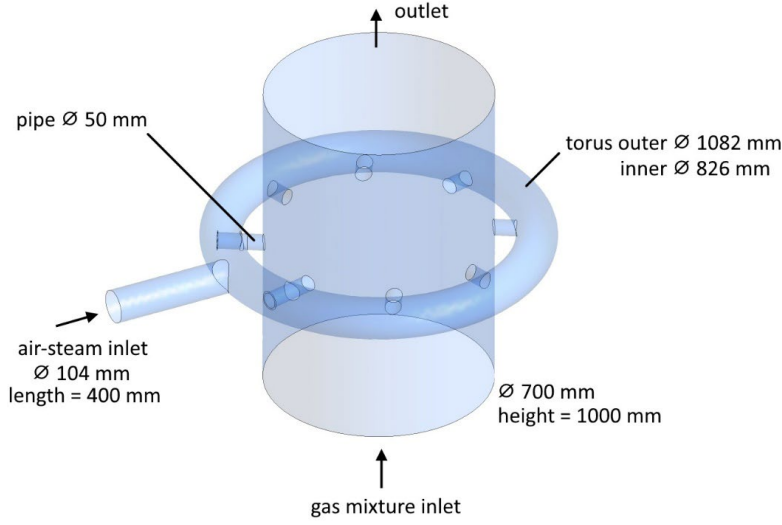


Fig. 2. A sketch of the ring collector model.

At the bottom of the model in Fig 2, a gas mixture (CO – 45 %, N₂ – 26 %, CO₂ – 16 %, H₂O – 6 %, CH₄ – 6 %, H₂ – 1 %) at 873 °C is introduced at a constant mass flow rate consistent with operating conditions. This gas flow drives the co-current flow of the gasifier. Additionally, a mixture of air and steam is introduced at 1073 °C from the pipe that connects to the collector ring, also

at a constant mass flow rate. The mixing of these two flow sources and the resultant velocity field determines the flow through the gasifier, modelled as the cylinder in the middle. The collector ring has eight symmetrically located inlet pipes that connect to the gasifier. These pipes will be subject to modifications throughout the study.

3. DESCRIPTION OF THE MATHEMATICAL MODEL

3.1. Governing Equations

The dynamics of the gas flow is described by the compressible Navier

Stokes equation:

$$\frac{\partial}{\partial t} \rho \vec{u} + \nabla \cdot (\rho \vec{u} \otimes \vec{u}) = \nabla \cdot \left(\mu \left(\nabla \vec{u} + (\nabla \vec{u})^T - \frac{2}{3} (\nabla \cdot \vec{u}) I \right) \right) - \nabla p + \rho \vec{g},$$

where ρ – density, $\vec{u}$ – velocity, μ – dynamic viscosity, p – pressure, $\vec{g}$ – acceleration of gravity, I – identity tensor. Here we use the Stokes hypothesis where the bulk viscosity is set to zero. The gas density is calculated by using the ideal gas relation:

$$\rho = \frac{1}{RT} p,$$

where R – ideal gas constant, T – temperature, p – pressure. The inlet gases are expected to be at different temperatures; therefore, the temperature is also solved by using an energy transport equation. The

gas species are transported, and they experience turbulent mixing. The diffusivity of the gases is taken as a sum of the regular diffusivity and turbulent diffusivity that is calculated using a turbulence model. The gas species are transported by using a transport equation that uses the flow velocity.

3.2. Numerical Models

3.2.1. Ring Collector Model

Calculations for the ring collector were done by using ANSYS Fluent 18. The gases were modelled as ideal gases, where the viscosities, diffusivities, thermal conductivities, specific heats, and molar masses were taken from the built-in Fluent database. Turbulence was modelled using the model.

For the ring collector model, chemi-

cal reactions of the gas are also considered, with the reaction rates determined by the Arrhenius equation. A summary of the chemical reactions is given in Table 1.

In this model, temperature iso-surfaces are examined to estimate the reaction fronts, with the aim of characterising slag deposition.

Table 1. Summary of Chemical Reactions Implemented in the Ring Collector Model

Reaction type	Reaction equation	A	E, J/kmol	Reference
volumetric	$\text{CO} + 0.5\text{O}_2 \rightarrow \text{CO}_2$	2.239×10^{12}	1.67×10^8	[12]
volumetric	$\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$	9.87×10^8	3.1×10^7	[13]
volumetric	$\text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$	5.12×10^{-14}	2.73×10^4	[2]
volumetric	$\text{H}_2 + \text{CO}_2 \rightarrow \text{CO} + \text{H}_2\text{O}$	1.785×10^{12}	3.26×10^8	Equilibrium with reaction #2
volumetric	$\text{CH}_4 + 1.5 \text{O}_2 \rightarrow \text{CO} + 2\text{H}_2\text{O}$	5.012×10^{11}	2×10^8	[14]
volumetric	$\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$	5.922×10^8	2.09×10^8	[15]

3.2.2. Gas Mixer Model

Preliminary calculations for the gas mixer were also performed using ANSYS Fluent 18. $k - \epsilon$ turbulence model was used for the steady-state calculations and Large Eddy Simulation (LES) [10] with the WALE sub-grid model [11] for transient simulations.

The model of gas mixer was also implemented in OpenFOAM-v2112 [16], which is an open-source library that specialises in modelling fluid dynamics. It uses the finite volume method to discretize the governing

equations. The *reactingFoam* module is used as the solver for the fluid flow, with the combustion disabled. This solver is used because it can model turbulent mixing for any number of gases. The viscosity of each species is calculated by using a variation of the Sutherland's law:

$$\mu = \frac{A_s \sqrt{T}}{1 + T_s/T},$$

where A_s – Sutherland coefficient, T_s – Sutherland temperature. The coefficients

were calculated by using the least-squares regression for the viscosity formula, where the ground truth data was taken from the NIST Chemistry webbook [17]. The specific heat of each species is calculated by using the JANAF thermochemical data [18] where the coefficients are taken from the GRI-mech 3.0 [19]. Thermal conductivity is calculated using the Eucken approximation [20]:

$$\kappa = \mu \cdot C_v \cdot \left(1.32 + 1.77 \cdot \frac{R}{C_v}\right),$$

where κ – thermal conductivity, C_v – specific heat.

The sub-grid turbulence was modelled using the LES k-equation model [21]. The species transport equation has a turbulent diffusion term that uses the turbulent viscosity as the local turbulent diffusivity value.

In this model, various types of standard deviations (which will be described in the next chapter) are being utilized to characterise the quality of mixing.

4. RESULTS OF THE MIXER MODEL

The first section of this chapter provides an overview of the standard deviation types used in the analysis of our study results. Next sections describe the results of the numerical simulations for two and three gas

mixing cases. The last section of this chapter attempts to analyse the varying levels of mixing efficiency observed within the context of our research.

4.1. Description of the Standard Deviation Types

There are different standard deviation types used across the results sections of the gas mixer model. Here they are briefly defined. The regular mean is defined as

$$\bar{x} = \frac{\sum_i^N x_i}{N},$$

where x_i – field value, N – number of values. The regular standard deviation is defined as

$$\sigma = \sqrt{\frac{\sum_i^N (x_i - \bar{x})^2}{N - 1}},$$

where $\bar{x}$ – the regular mean, N – number of values. The area-weighted mean is defined as

$$\bar{x}_w = \frac{\sum_i^N a_i x_i}{\sum_i^N a_i},$$

where x_i – the field value in the i -th cell, a_i – the cell area, N – the number of cells. The area-weighted standard deviation is defined as

$$\sigma_w = \sqrt{\frac{\sum_i^N a_i (x_i - \bar{x}_w)^2}{\frac{M - 1}{M} \sum_i^N a_i}},$$

where $\bar{x}_w$ – area-weighted mean, M – the number of non-zero-weights (cell areas). In our case there are no non-zero weights; therefore, M is equal to N .

The gas concentration data is sampled on OXY planes that slice the pipe. The mixing uniformity is quantified in three ways:

The mean value of the spatial standard deviation at each point in time:

$$\frac{1}{K} \sum_j^K \sigma_w^j,$$

where j – timestep index, K – the number of timesteps, σ_w^j , the area-weighted standard deviation for the j -th timestep.

The regular standard deviation for the area-weighted spatial mean in each point in time:

$$\sqrt{\frac{\sum_j^K (\bar{x}_w^j - \bar{x}_w^*)^2}{K-1}},$$

where j – the timestep index, K – the number of timesteps, $\bar{x}_w^*$ – the mean value of the weighted spatial mean over all timesteps.

4.2. Mixing of Two Gases

The full gas mixer has a geometry with many places that require a high-resolution mesh to accurately model the fluid flow. The mixing process takes place in many identical pipes (Fig. 1a); therefore it was decided to examine a single one of these pipes (Fig. 1b) instead of the whole reactor. From the geometry of the mixer, it is expected that the pressures near the inflows of the pipes are very similar for each pipe. This leads us to the belief that all these pipes behave in a similar way, which justifies considering only one pipe.

In the geometry shown in Fig. 3d, there are two gases that are introduced. Before modelling the mixing of three gases it is useful to see the qualitative behaviour of the mixing of two gases. Oxygen is injected through the top part of the central cylinder, and methane is injected from the outer sur-

The area-weighted mean value of the regular standard deviation of over time for each cell:

$$\frac{1}{\sum_i^N a_i} \sum_i^N \left(a_i \sqrt{\frac{\sum_j^K (x_i^j - \bar{x}_i)^2}{K-1}} \right),$$

where j – timestep index, K – number of timesteps, $\bar{x}_i$ – the mean value over time for the i -th cell, x_i^j – the value in the i -th cell in the j -th timestep.

face of the surrounding chamber. The outlet is the bottom surface of the central cylinder.

The initial calculations presented in Figure 4 were done in ANSYS Fluent. Figure 4 shows a comparison of a steady state solution and a snapshot of a transient solution using LES, where both cases have the same flow parameters. There are clear differences between both cases – the steady state solution shows that both gases mix quickly and have a very uniform distribution in the pipe, however the transient solution shows that there are turbulent pulsations near the top that cause the concentrations to fluctuate both in the transverse and lengthwise directions. This comparison demonstrates that steady state RANS models overestimate the uniformity of mixing, because they do not account for transient changes in velocity and concentration.

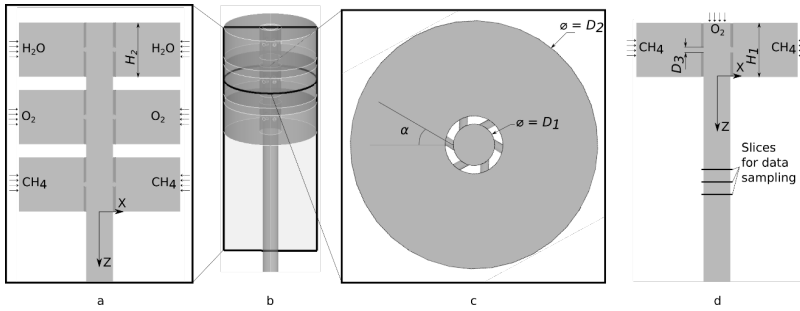


Fig. 3. Simulation domain for a single mixer pipe with 6 holes: a) three gas model, vertical cross section, b) three gas model, 3D view, c) three gas model, horizontal cross section, d) two gas model, vertical cross section. $D_1 = 18$ mm, $D_2 = 60$ mm, $D_3 = 2$ mm, $H_1 = 20$ mm, $H_2 = 40$ mm. Drawings are not to scale.

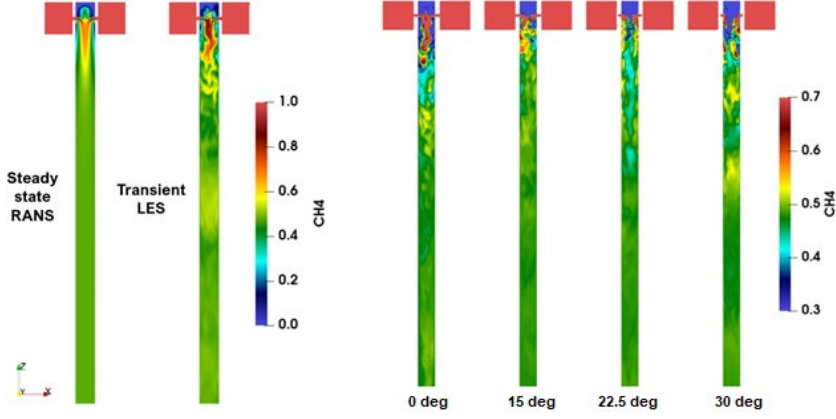


Fig. 4. On the left: Comparison between the CH_4 mass fraction in a vertical cross section for solutions in ANSYS Fluent: a steady state RANS () solution and a transient LES solution at a randomly chosen timestep. On the right: Comparison between CH_4 mass fractions in a vertical cross section for transient LES simulations in OpenFOAM for different hole angles for 6 holes: 0 degrees, 15 degrees, 22.5 degrees, 30 degrees.

It is important to note that the mixing takes place not only inside the mixer zone, but all the way further down the central pipe. The gas flow is highly turbulent which leads to intense mixing. Figure 5 shows the relative standard deviations for different distances from the bottom chamber. The distance from the bottom chamber is the Z coordinate shown in Fig. 3. As expected, the mixture becomes more uniform as it flows down the pipe and mixes due to the turbulence. The highest of the observed deviation types is the temporal, meaning that changes over time are more pronounced than over cross section of the main pipe. For this case, the data were collected starting from distance of 10 cm from the bottom chamber.

The variations are below 3 % for all deviation measures at the distance of 10 cm.

It is also useful to see whether the angle of the holes influences the result in a meaningful way. The azimuthal hole angle is taken as the angle between the axis of the hole and normal of the main cylinder surface (α in Fig. 3c). Here the hole positioning stays the same, but each of the cylindrical holes gets rotated in place. Figure 4 (right) shows snapshots of transient simulations for varying azimuthal hole angles.

The data are sampled on an OXY plane that slices the pipe 15 cm below the last chamber (see Fig. 3d). The mixing uniformity is quantified in three ways which have been described in the previous section.

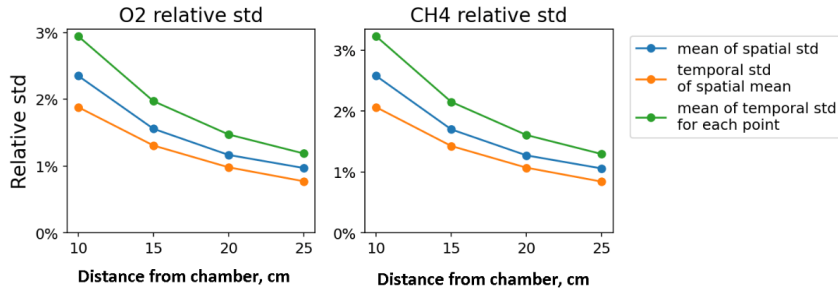


Fig. 5. The relative standard deviations for the O_2 and CH_4 mass fractions at horizontal section planes at different distances from the bottom chamber. The two gas mixer.

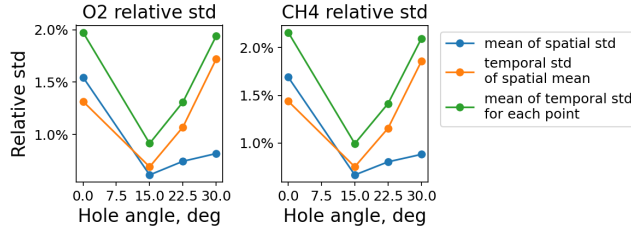


Fig. 6. The relative standard deviations for the O_2 and CH_4 mass fractions at the section plane for a varying azimuthal angle.

Figure 6 shows the relative standard deviations for varying azimuthal angles. It is noticeable that there is a clear optimal angle at which all of the standard deviations of the methane mass fraction are the lowest. Increasing the angle further leads to poorer

mixing, which can be explained by the fact that a larger angle directs the injected gas more towards the outer part of the pipe. If the angle is too large, then the injected gas gathers on the outer part of the pipe which leads to less mixing.

4.3. Mixing of Three Gases

The full mixer geometry mixes three gases – steam, oxygen and methane. Figure 3 a-c shows the geometry of a mixer pipe for three gases. Steam flows in through the top chamber, oxygen flows through the middle chamber and methane flows through the bottom chamber. Unlike before, the topmost gas is pumped in through a chamber that is directly connected to the central pipe.

The initial geometry starts with 6 evenly spaced holes that are perpendicular to the cylinder for both the middle and bottom chambers. The data are sampled the same way as in the two-gas case. To see how the length of the mixing pipe influences the result, the data were sampled on multiple OXY slices at different distances from the last chamber.

Figure 7 shows the relative standard deviations for the different distances from

the last chamber. As expected, the mixture becomes more uniform as it flows down the pipe and mixes due to the turbulence. The distance of interest for our mixer geometry is 15 cm; therefore, the optimisation will be based on the values at that slice. It is expected that the optimum mixer shape for the slice at 15 cm will also be the optimum mixer shape for distances further along the pipe.

For the three gas mixer the spatial deviation dominates over temporal deviation. It is mostly visible at the beginning of the main pipe, close to bottom chamber. The difference to two gas mixing model, where temporal deviation dominates, is likely due to different gas inflow conditions. For the two gas mixer, O_2 was supplied from the top face of the model, whereas in three gas model – via middle chamber.

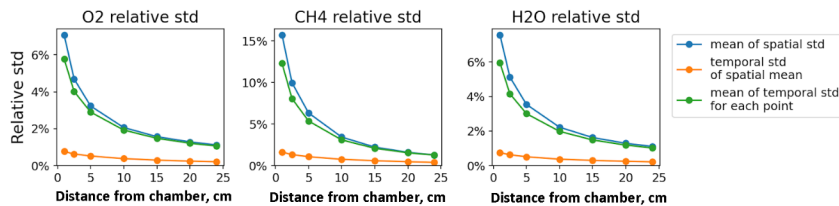


Fig. 7. The relative standard deviations for the O_2 and CH_4 mass fractions at horizontal section planes at different distances from the bottom chamber. The three gas mixer.

It is expected that the number of holes at the bottom chamber plays the biggest role on the mixing because it is at the point where all three gases meet. The number of holes is also inversely proportional to the cross-flow jet velocity which in turn influences the distribution of gases and the turbulence in the central pipe near holes. The number of holes on the bottom chamber is varied from 3 to 8.

Figure 8 shows the relative standard deviations for the number of holes at the bottom chamber. For 5 holes, the spatial relative standard deviations are at a minimum. The temporal relative standard deviations decrease until 5 holes and have negligible changes for larger hole counts. Next the number of holes on the top chamber are varied from 3 to 12. The flow near the top

holes is expected to be slower than the flow at the bottom holes; thus, more holes might be needed to reduce the cross-flow velocity.

Figure 9 shows the relative standard deviations for the number of holes at the top chamber. The results are less clear than for the bottom holes as there is no clear minimum across the three gases. The spatial standard deviation changes unpredictably, with a slight positive trend, and the temporal standard deviations increase if the number of holes is too small. A value of 6 holes is chosen as an optimal value, judging from the O_2 and H_2O (steam) graphs. The CH_4 standard deviations are less affected by varying the number of holes, which is explained by the fact that it is being injected by the holes at the bottom chamber and not at the top.

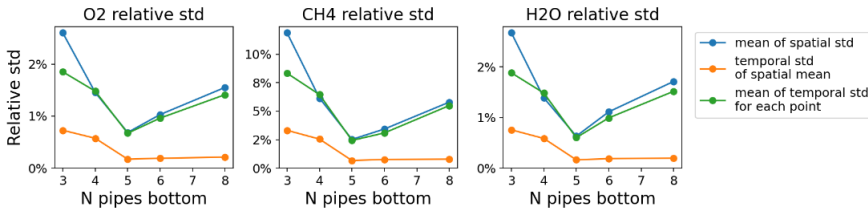


Fig. 8. The relative standard deviations for the O_2 , CH_4 and H_2O (steam) mass fractions at the section plane for varying number of holes for the bottom chamber.

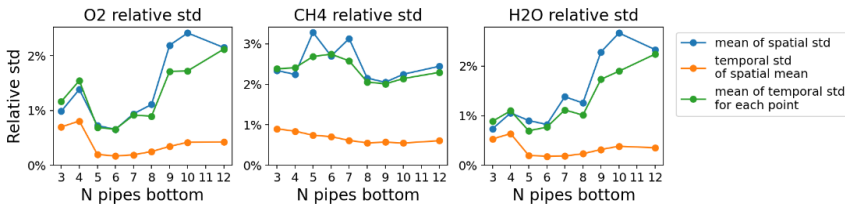


Fig. 9. The relative standard deviations for the O_2 , CH_4 and H_2O (steam) mass fractions at the section plane for varying number of holes for the top chamber.

Comparing the effects of the number of holes at the bottom and top chambers it is apparent that the bottom number of holes has much greater effect on the mixing uniformity. This can be explained by the fact that the introduced CH_4 cross-flow is also

surrounded by partially mixed H_2O and O_2 that are then mixed a second time. The bottom cross-flow essentially mixes all three gases instead of just two.

Figure 10 shows the relative standard deviations for varying azimuthal angles of

the holes at the bottom chamber. The results show that increasing the azimuthal angle reduces the mass fraction standard deviations for all three species, and for large angles above 45 degrees the standard deviation increases again. The measured differences for varying angles are only within one percent. Compared to varying the number

of holes, varying the azimuthal angle of the holes gives a smaller effect on the mixing uniformity. This might be because the optimum number of holes for the top and bottom chambers has already been chosen, thus varying the azimuthal angle at a chamber gives less of an improvement.

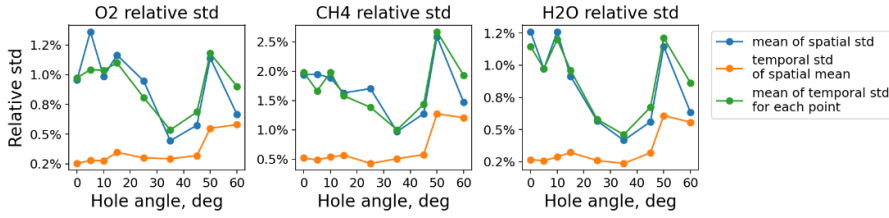


Fig. 10. The relative standard deviations for the O₂, CH₄ and H₂O (steam) mass fractions at the outlet for varying azimuthal hole angles at the bottom chamber.

4.4. Discussion on the Different Mixing Efficiencies

Figure 11 shows iso-contours for methane for the mixer with 3, 5 and 8 holes. The key difference is that the number of holes influences the velocity at which the gas gets injected into the central pipe. In the 3-hole case the velocities are large, and the methane gets shot to the centre of the pipe while the other gases flow on the outside. In the 8-hole case the velocities are lower and the methane gets immediately pulled by the other gases downwards while it is still

on the outer part of the pipe. In the 5-hole case, the scenario is somewhere in between where methane gets distributed more evenly throughout the volume.

Figure 12 shows iso-surfaces for different hole angles. The angle adds rotation to the flow which can smooth out any radial asymmetries in the concentrations, however making the angle too big will push the gas to the outer wall of the pipe and impede mixing.

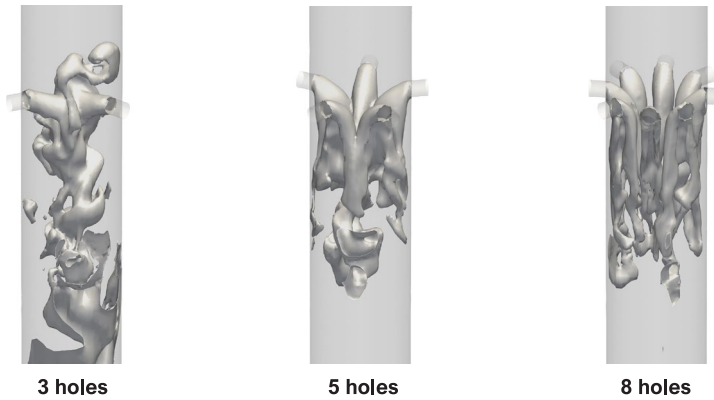


Fig. 11. CH₄ iso-surfaces near the chamber for a different number of holes.

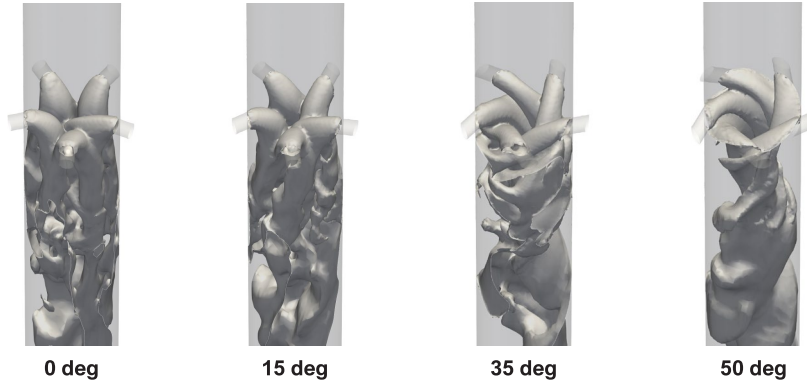


Fig. 12. CH_4 iso-surfaces for different hole angles in the azimuthal direction.

5. RING COLLECTOR RESULTS

At the start, a simulation was run for the default geometry of the gasifier, which simply included eight inlets symmetrically located around the collector ring. As asymmetric slag deposition had been observed in the gasifier, the aim was to determine the cause for this asymmetry. Upon conducting simulations, it was determined that a constant mass flow through the collector pipe did not supply a uniform mass flow throughout the inlet pipes to the gasifier. The inlet pipe numbering and the mass flow distribution is shown in Fig. 13.

One can immediately notice that the flow is severely weaker through inlets 1 and 8. This eventually causes asymmetry in the system, as the remaining inlets push the entire flow towards the wall where inlets 1 and 8 are located. This is well illustrated with the temperature iso-surface in Fig. 14. The iso-surface is tilted towards one side of the gasifier. In terms of slag formation, this is undesirable, as different temperatures along the walls of the gasifier also mean different levels of the ash melting intensity and thus different rates of slag deposition.

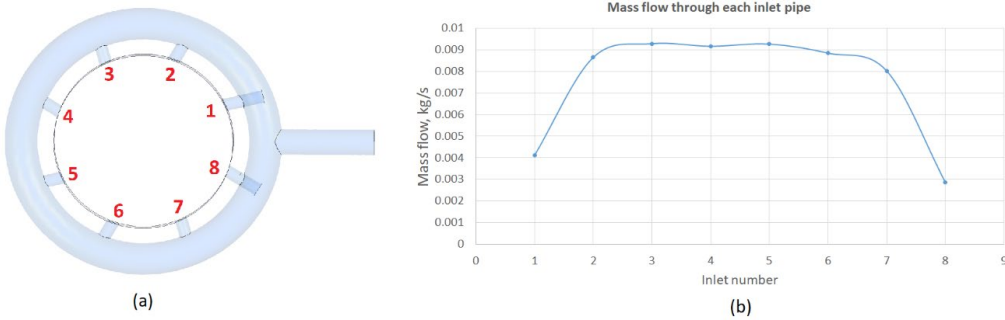


Fig. 13. (a) The numbering convention for inlets, (b) mass flow distribution for the inlet pipes for the default geometry.

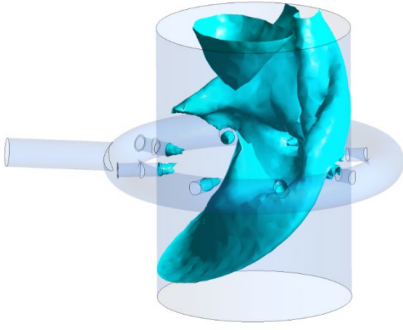


Fig. 14. Temperature iso-surface (900 °C) for the default case.

To combat this, the flow from the inlet pipes should be as close to uniform as possible. In practice, this means modifying the collector ring. The reason for the mass flow rate drop at inlets 1 and 8 is mainly the high velocity of the gas flow that arrives from

the main collector pipe. Therefore, the flow before these inlets should be broken up to achieve higher uniformity.

Multiple solutions were tested, and the best results were obtained with one of the two modifications – a small obstacle added to the inner wall of the collector directly before inlets 1 and 8 (Fig. 15a), or the extension of inlet pipes inside the collector with holes inside those extensions (Fig. 15b).

Upon implementing these solutions, the symmetry of the flow improved significantly. Even though the mass flow through the inlets was not entirely uniform, it was markedly improved from the initial case as shown in Fig. 16 b, and the flow was sufficiently symmetrical to no longer have any tilt of the temperature iso-surface (Fig. 16a).

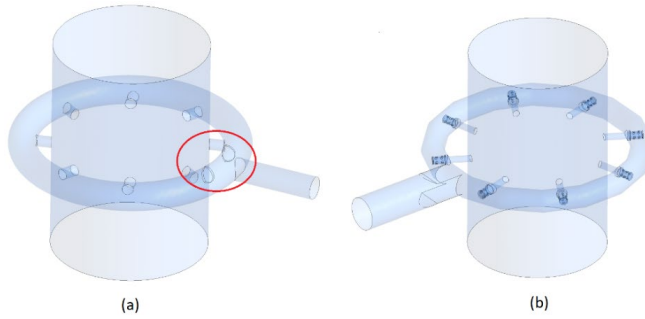


Fig 15. Geometry for (a) an obstacle for collector inner wall, (b) inlet pipe extensions.

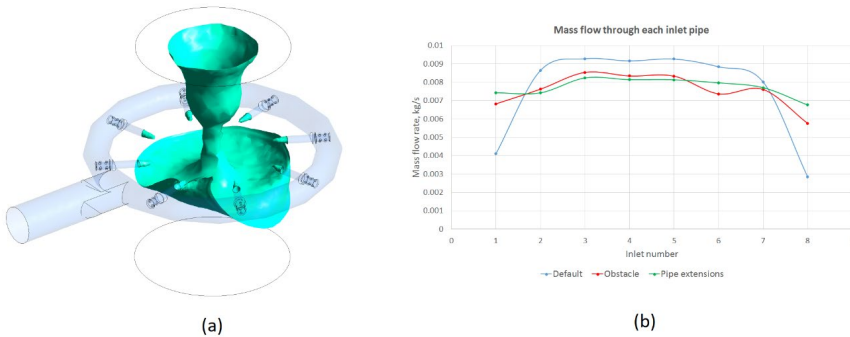


Fig. 16. (a) Temperature iso-surface (900 °C) for the improved geometry, (b) mass flow distributions for the improved geometries in contrast to the default geometry.

The obtained improvements for mass flow distributions can be explained by two factors. In the model with obstacle

(Fig. 15a), local high-pressure spots were reduced. These were caused by the fluid flow, which after the 90-degree turn was

pushed towards the region of closest pipes (1 and 8). Obstacles did not allow flow to be pushed towards the pipes, thus improving the uniformity.

The second factor leading to the uniformity of the mass flow through pipes is the ratio of hydraulic resistance of pipes (R_p Fig 17) to that of the collector ring sectors (R_s in Fig. 17). The hydraulic resistance is estimated using an approximation of the Colebrook-White equation developed by Bellos et al. [22]. Here we neglected the relative roughness factor, leaving an expression for smooth pipes:

$$f = \left(\frac{64}{Re}\right)^a \left(0.75 \ln\left(\frac{Re}{5.73}\right)\right)^{2(a-1)}$$

$$a = \frac{1}{1 + \left(\frac{Re}{2712}\right)^{8.4}}$$

where f is the friction factor in the equation for head loss:

Using these data, the ratio $R_p/R_s = 0.602$, meaning that the hydraulic resistance of the sector is larger than that of the pipe. The pipe extensions increase the length and

decrease the diameter of the pipe, leading to the increased ratio $R_p/R_s = 3.680$.

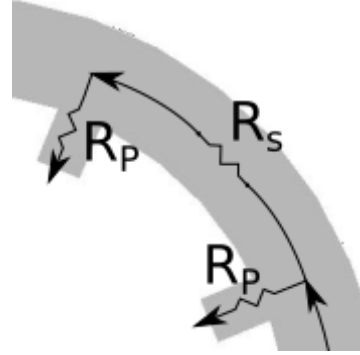


Fig. 17. Schematic illustration of hydraulic resistances in the collector ring model. R_s is the resistance to flow along one sector of the ring. R_p is the resistance of one pipe.

Eventually, the solution with pipe extensions was implemented in the real-life version of the gasifier. After running a test with the new inlet configuration, it was indeed determined that asymmetrical slagging had significantly decreased. This proves the premise that the flow regime was what caused the asymmetrical slagging in the first place, and that ensuring a uniform flow through the inlets is crucial to prevent undesirable slagging.

6. CONCLUSION

In summary, this research underscores the effectiveness of numerical simulations in explaining the flow characteristics within gas mixing systems crucial for energy conversion processes. The following aspects have been concluded during this study:

1. The study has exposed the limitations of steady-state RANS models in assessing gas mixing uniformity. These models, by neglecting transient flow changes, can overestimate the mixing uniformity,

failing to capture the dynamic variations in local gas concentrations over time.

2. Critical factors affecting gas mixing uniformity have been identified – the number of holes along the mixing pipe's circumference and the azimuthal angle of these holes relative to the central cylinder. The number of holes impacts the cross-flow velocity, while the azimuthal angle influences gas distribution within the cross-flow region.

3. The gas mixer model has revealed that mixing occurs along the pipe length, with turbulence introduced at the holes near chambers enhancing uniformity. It is important to note that the pipe length must be carefully considered, as overly short pipes may yield uneven mixtures, while longer ones often face design constraints.
4. Contrasting the idealised gas mixer model, the industrial ring collector calculation has shown varying flow rates through the holes. Importantly, we have demonstrated that solving these issues can be accomplished without major equipment modifications.
5. For the ring collector, it has been concluded that the asymmetrical slag deposition can be sufficiently explained by the asymmetrical flow of the gas in the gasifier and gas-gas reactions. Particle-gas reactions were observed to have a relatively minor impact, with flow characteristics playing a more dominant role in this asymmetrical slag deposition. It has also been shown that ensuring the hydraulic resistance of pipes to be larger than that of the collector ring can enhance the uniformity of the gas flow.
6. To remove the undesirable asymmetrical slag deposition, it is necessary to construct inlet configurations that promote the axi-symmetrical flow.

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