

1 Highlights

2 **Computationally inexpensive CFD modeling of sewage sludge and waste additive combustion exper-** 3 **iments in an entrained flow reactor**

4 Benjamin Ortner, Christian Schmidberger, René Prieler, Christoph Hochenauer

- 5 • Insights into waste-based combustion with additives in an entrained flow reactor
- 6 • The effect of additives used to adjust the basicity ($B_1 = CaO/SiO_2 \approx 1$) is discussed
- 7 • Novel, computationally inexpensive CFD model proves useful for up-scaling
- 8 • Very good match between experimental and simulated results
- 9 • Meat and bone meal significantly affects combustion behavior and heat release

10 Computationally inexpensive CFD modeling of sewage sludge and waste additive 11 combustion experiments in an entrained flow reactor

12 Benjamin Ortner^a, Christian Schmidberger^b, René Prieler^a, Christoph Hochenauer^a

13 ^a*Institute of Thermal Engineering, Faculty of Mechanical Engineering and Economic Sciences, Graz University of Technology,*
14 *Inffeldgasse 25B, 8010 Graz, Austria*

15 ^b*Institute of Combustion and Power Plant Technology, Faculty 4 - Energy-, Process- and Bio-Engineering, University of Stuttgart,*
16 *Pfaffenwaldring 23, 70569 Stuttgart, Germany*

17 Abstract

18 A computationally inexpensive, mixture-fraction-based CFD model was applied to investigate the combustion char-
19 acteristics of two types of sewage sludge powder. These were mixed with meat and bone meal (MBM) and cement
20 bypass dust (BPD) as additives. Experiments on a semi-industrial furnace were performed to obtain validation data.
21 A wide range of operating conditions across eight different scenarios, varying by sludge type, additive combinations,
22 and combustion settings, including over- and substoichiometric conditions as well as slight oxygen-enhancement
23 were tested. All fuel-additive mixtures were adjusted to a basicity ($B1 = CaO/SiO_2$) of one. Numerical simula-
24 tions of entrained flow combustion were performed, and the CFD model's predictions were validated against the
25 experimental measurements and observations. Results showed that MBM had a significant impact on combustion
26 behavior. When MBM was used to adjust the basicity, it increased the heat release in the furnace by up to 57% for
27 sewage sludge with a lower initial basicity. This effect was attributed to the higher heating value of MBM. However,
28 the MBM also displayed a slower burnout rate compared to sewage sludge powder with BPD, indicated by spatial
29 trends in the gas phase measurements. This was likely due to the larger particle size of the MBM. In contrast, BPD
30 had a negligible impact on combustion behavior. Overall, the CFD model demonstrated very good agreement with
31 the experimental data, confirming its effectiveness as a tool for research, development, and process up-scaling.

32 *Keywords:*

33 Sewage sludge, Meat and bone meal, CFD modeling

34 1. Introduction

35 During recent years increased efforts have been made in the field of the recovery of valuable ingredients from
36 waste products. Sewage sludge was increasingly used for thermal utilization [1] instead of direct application in
37 agriculture. Furthermore, sewage sludge, often overlooked as a waste product, holds both substantial energy content

Email address: benjamin.ortner@tugraz.at (Benjamin Ortner)

38 and the potential for reclaiming valuable resources - especially phosphorus [2]. The essential nutrient phosphorus
39 is classified as a critical raw material by the European Commission due to Europe's heavy reliance on imports
40 [3, 4]. Ways of thermal treatment where valuable ingredients are recovered from ashes, seem especially interesting
41 in this regard. Sewage sludge ash can contain P_2O_5 in the range of up to 26%, with the average being 15% [5, 6].
42 This relates to around 6.5% of pure phosphorus on average (weight-%). Hence, there is a strong need to develop
43 efficient methods for phosphorus recovery from sewage sludge, aligning with the principles of a circular economy. In
44 addition to sewage sludge, other residues, such as waste from the meat industry, can also serve as valuable sources
45 of phosphorus. Staroń et al. [7] report that meat industry waste contains approximately 30–170 g of phosphorus per
46 kilogram of ash. Their study also highlights that these ashes are rich in calcium, with levels ranging from 20 to 360
47 g per kilogram of ash. However, in the thermochemical recycling of sewage sludge, the raw phosphorus or calcium
48 content per kilogram of waste material is not the only consideration. Factors such as the material's composition
49 — particularly its basicity — play an important role in determining the efficiency of recovery processes. Meat
50 and bone meal (MBM) can therefore not only serve as a phosphorus source but also influence the recovery rate
51 positively. However, MBM is an organic-containing additive that changes the combustion characteristics of the
52 fuel mixture. A notable amount of studies have been performed on MBM combustion, often on co-combustion and
53 gasification with coal [8–11]. A performance analysis in terms of the drying process, pyrolysis and the kinetics of
54 volatile combustion was performed by Kantorek et al. [12]. An energy balance and greenhouse gas accounting for
55 the pyrolysis and gasification of MBM were provided by Cascarosa et al. [13].

56 Cement bypass dust (BPD) is a waste material originating from cement production plants. It contains a large
57 fraction of calcium oxide [14]. It is interesting because - unlike MBM - it is not expected to substantially influence
58 the major in-furnace behavior of the mixtures such as gas phase compositions and temperature profiles. However,
59 it can impact the slag characteristics significantly. Therefore, this study aims to explore how the application of two
60 very different additives for basicity adjustment influences the combustion behavior of sewage sludge in entrained
61 flow combustion under various operating conditions. A computational fluid dynamics (CFD) modeling approach,
62 combined with experimental validation, is used to analyze the combustion process of sewage sludge when mixed
63 with MBM and BPD additives, offering insights into their effects on combustion performance.

Nomenclature

Abbreviations

ar	as received
BAL	Balingen sludge
BPD	Cement bypass dust
CFD	Computational fluid dynamics
daf	Dry, ash-free
DIA	Dynamic image analysis
DPM	Discrete phase model
DRW	Discrete random walk
EAR	Excess air ratio
EDC	Eddy dissipation concept
EDM	Eddy dissipation model
LHV	Lower heating value
LES	Large eddy simulation
MBM	Meat and bone meal
MFC	Mass flow controller
PSD	Particle size distribution
RRSB	Rosin-Rammler-Sperling-Bennett (PSD)
SFM	Steady diffusion Flamelet
STR	Straubing sludge
TC	Thermocouple
WSGGM	Weighted sum of gray gases model

Greek symbols

ρ	Density
ϵ	Turbulence dissipation rate
ε	Emissivity
ψ	Sphericity (Wadell)
μ, μ_t	Dynamic viscosity, turbulent viscosity

Roman symbols

$B1$	Basicity
c_P	Specific heat (constant pressure)
f	Mean mixture fraction
f'^2	Mixture fraction variance
$\vec{g}$	Gravity
H	Enthalpy
k	Turbulence kinetic energy
k_t	Thermal conductivity
S	Source term
t	Time
$\vec{v}$	Velocity vector
Z	Mass fraction

Subscripts

$fuel$	Fuel
ox	Oxidizer

65 The recovery process of phosphorus from sewage sludge typically begins with the thermal conversion of mostly
66 pre-dried and ground sludge in a furnace. A review on thermochemical conversion of sewage sludge was provided
67 by Gao et al. [15]. In this study, the focus lies on the behavior in so-called entrained flow furnaces where the
68 fuel is injected with carrying air and often mixed with a secondary oxidizer. The secondary oxidizer is created by
69 mixing air with pure oxygen to increase the overall O_2 concentration. This process usually involves a high level of
70 turbulence. CFD studies on the thermal processing of waste are not uncommon. Often MBM or municipal solid
71 waste are considered in the context of their application in cement kilns [16, 17], where the waste is co-combusted
72 with coal. Because of the obvious similarities (water content, volatiles, fixed carbon, ash), the combustion of sewage
73 sludge, as well as MBM, have often been simulated based on modeling approaches from the field of pulverized coal
74 combustion, for instance using the eddy-dissipation model (EDM) [18]. Ogada et al. described the combustion
75 behavior of sewage sludge within a fluidized bed, highlighting that 90% of the ash-free components are emitted as
76 volatiles [19]. They also remark that the combustion behavior of sewage sludge closely resembles that of gaseous
77 fuels [20]. Additionally, Cui et al. observed that particle dehydration and devolatilization can occur simultaneously
78 [21]. Surrogate approaches were applied for small-scale sludge incineration plants [22], also with reduced chemical
79 kinetics [23]. In our previous study, we applied the steady flamelet model (SFM) considering the influence of
80 limestone additives and variations in water content [24]. The computational efficiency of this approach allowed the
81 application of large eddy simulations (LES) of the considered furnace [25]. MBM should be expected to behave
82 comparably in an entrained flow furnace, which is why similar CFD modeling approaches have been taken, for
83 instance for modeling the combustion of chicken litter and MBM in a drop tube furnace featuring swirling flow.
84 The eddy dissipation concept (EDC) model was used to consider chemistry in the study of Heikkinen et al. [26].
85 The combustion of MBM together with coal in a cement rotary kiln has been investigated using CFD simulations
86 with a focus on the particle size and fuel feeding position. It was noted that large particle sizes and higher fixed
87 carbon contents result in reduced char burning [27]. The ash deposition for the co-combustion of MBM with coal
88 was investigated by Taha et al. [28] as a post-processing step for a combustion model. A numerical simulation of the
89 deposition of fly ash particles in a cyclone furnace was performed by Bai et al. [29]. In summary, numerous studies
90 have modeled sewage sludge or MBM combustion. This study aims to contribute a CFD-supported investigation of
91 the key effects of sewage sludge combustion in an entrained flow reactor, considering the influence of MBM and BPD

additives. A wide range of operating conditions is explored, including substoichiometric combustion and oxygen enhancement.

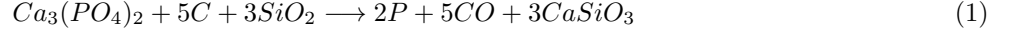
2. Experiments

This section is about the collection of experimental data for the validation of the CFD model. Tab. 1 shows the elementary and proximate analysis of the investigated materials. Four different powdered materials were used in total. Through a drying and grinding process, the mass-based water content of the fuels was brought down to 10% or lower for all fuels. The sewage sludge from Straubing, Germany - in the following denoted as STR - has high volatile- and fixed carbon fractions of 57% and 7.7% respectively, due to a low ash fraction of 26.9%. The sludge from Balingen, Germany (denoted as BAL) has a higher ash content and therefore, volatile- and fixed carbon fractions are lower at around 40.9% and 4.1% respectively. On an ash-free basis, the proximate analyses are comparable. Also, the elementary analysis results of both sludge samples are similar. The lower heating value (LHV) on a wet basis, which describes the chemical energy contained per kg of fuel as received (ar), is considerably higher for STR sludge, which is expected to influence the combustion behavior significantly. The MBM sample on the other hand has a very low ash fraction of 18.1% and therefore an even higher LHV of 19.5 MJ/kg.

Table 1: Fuel analysis, ar = as received, daf = dry, ash-free

Fuel	Water content	Volatiles	Fixed carbon	Ash	C	H	O	N	S	LHV in MJ/kg
STR	8.4	57.0	7.7	26.9	49.1	6.7	34.1	8.4	1.7	13.0
BAL	10.0	40.9	4.1	45	50.8	6.8	34.1	6.4	1.9	9.2
MBM	2.3	68.5	11.1	18.1	54.9	7.4	24.6	12.2	0.9	19.5
Proximate analysis (ar)					Elementary analysis (daf)					

The background of this study is the thermochemical recycling of phosphorus from sewage sludge and other phosphorus-containing wastes through the Flashphos process [30]. The interested reader is referred to Häggström et al. [31] and Lidman Olson et al. [32] for in-depth discussions on the fate of phosphorus in entrained flow and phosphorus chemistry in the thermal conversion of biomass. The objective of the Flashphos process is to extract phosphorus in its elemental form through a two-stage process. In the first stage, sewage sludge is converted into gas and slag. Following this step, the slag is reduced in a state-of-the-art reduction furnace. For natural phosphorus-rich input materials, such as calcium phosphate, the reduction process can be described in a simplified way by the Wöhler reaction (1):



For this process, a basicity of $B1 = CaO/SiO_2$ of one is considered favorable, as the reagents in Wöhler reaction (1) follow approximately this ratio. This estimate was considered sufficient. The different additives are used to influence the basicity and may change the combustion characteristics, which is the focus of this study.

Besides influencing the process chemistry, additional CaO can also act as a flux to reduce the melting temperature and the viscosity, which is supposed to improve the flow characteristics of the slag that is generated in the combustion process at high temperatures. Both can be achieved using CaO -rich additives like MBM or BPD. An ash analysis is presented in Table 2, showing the primary compound fractions found in the ash samples. To achieve a basicity $B1$ of unity, a blend of sewage sludge powder and waste additive was formulated, resulting in a mixed powder with the desired basicity level. Consider BAL sludge, with an initial basicity of $B1 = CaO/SiO_2 = 16.1/31.5 = 0.511$. To achieve a basicity of $B1 = 1$, accounting for water content and organic fraction, 0.903 kg of MBM per kg of BAL sludge is required. Alternatively, adding 0.136 kg of BPD per kg of BAL sludge yields the same result. For STR sludge, due to its different initial basicity, 0.245 kg of MBM per kg of STR sludge and 0.038 kg of BPD per kg of STR sludge are needed.

Table 2: Ash analysis (weight-%, water- and organic free, 550°C)

Sample	SiO_2	CaO	P_2O_5	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3
BAL	31.5	16.1	14.2	16.7	16.7	3.15	1.68	-	-
STR	24.1	17.1	21.8	17.9	14.6	2.82	1.73	-	-
MBM	2.34	44.7	37.4	0.22	0.44	1.49	4.14	4.80	2.34
BPD	13.0	63.8	0.10	3.60	4.09	0.69	11.2	0.52	2.56

The particle size distribution (PSD) is likely to have a significant impact on the combustion behavior of the materials. Therefore, the PSD of the sludge and waste samples was determined using dynamic image analysis (DIA). The results are depicted in Fig. 1a for the sludge samples and Fig. 1b for samples of MBM and BPD. It is evident that there are significant differences in particle sizes among the samples. For instance, nearly 90% of BAL particles are smaller than 100 μm , whereas only around 50% of STR particles fall below this size threshold. Nonetheless, the STR powder is still considered fine compared to the MBM sample. The MBM sample contains particles as large as 1 mm, setting it apart from other organic-containing samples. Yet, the majority of particles are below 400 μm . The BPD shows a size profile comparable to that of the sludge samples. To model the experimental

data, a non-linear least squares method was used to fit a Rosin-Rammler (RRSB) distribution for subsequent CFD calculations. The resulting size (x') and spread parameters n are summarized in Fig. 1 for reference.

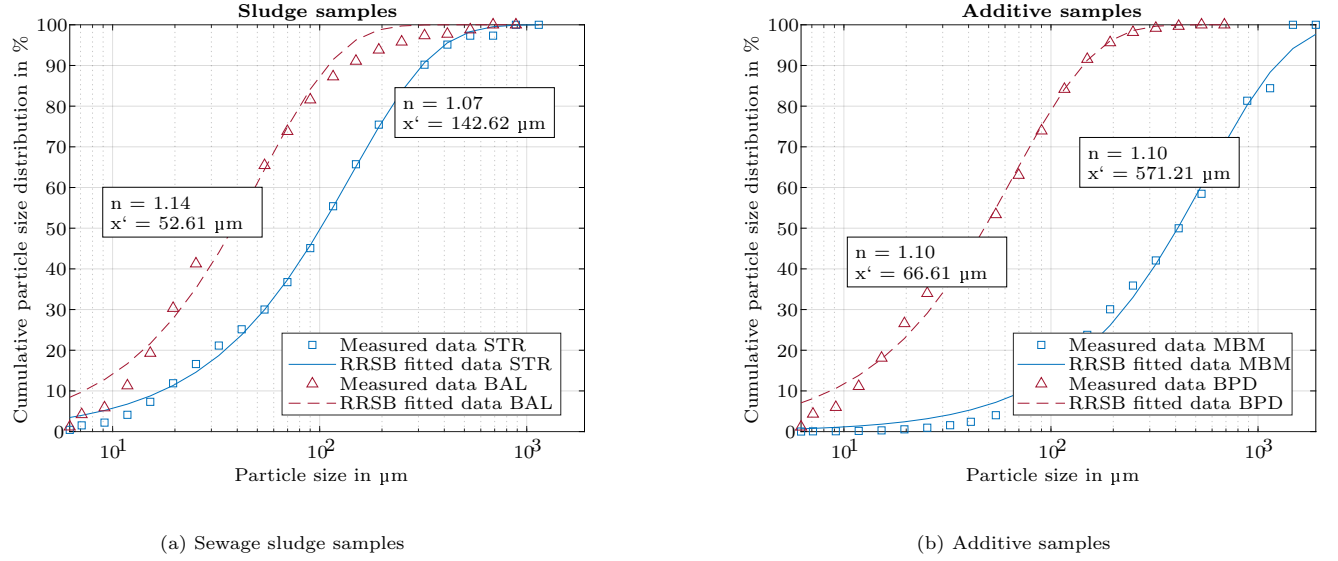


Figure 1: Particle size distributions measured with dynamic image analysis and RRSB fits

In Fig. 2, the unique experimental reactor, located at the University of Stuttgart, is depicted schematically. It is considered highly suitable for our trials as it can closely replicate the conditions of an upscaled system, including substoichiometric conditions and oxygen enhancement. It consists mainly of a vertically oriented ceramic drop tube with an inner diameter of 200 mm. The total length of the reaction chamber is 2.5 m, typically ensuring complete burnout of the material. Electric heating elements (T1-T5) are used to heat the walls of the drop tube, maintaining the wall temperature at 1300 °C during the experiments. At the top of the reactor, the injection system includes a fuel container, screw conveyor, pneumatic shaker, and conveying hoses, resting on a scale for precise measurement of fuel mass flow. The burner (see Fig. 3) injects the fuel, along with carrying air, into the reaction chamber, where it mixes instantly with oxygen-enhanced air (secondary oxidizer) from three nozzles positioned near the sewage sludge injection, ensuring rapid, turbulent mixing of fuel and oxidizer. The burner includes an additional annular inlet, occasionally used to maintain consistent gas velocities near the burner, as the stoichiometric air demand varies significantly with the fuel composition. The burner produces a non-swirling jet-type flame. The oxidizer flow is controlled using separate mass flow controllers (MFC).

Temperatures were measured using a vertically adjustable thermocouple with a ceramic shielding. It was inserted into the reaction zone from the top, slightly off-center and up to a distance of 0.35 m from the injection location. Due to the strong influence of thermal radiation and very pronounced slag depositions on the thermocouple, it

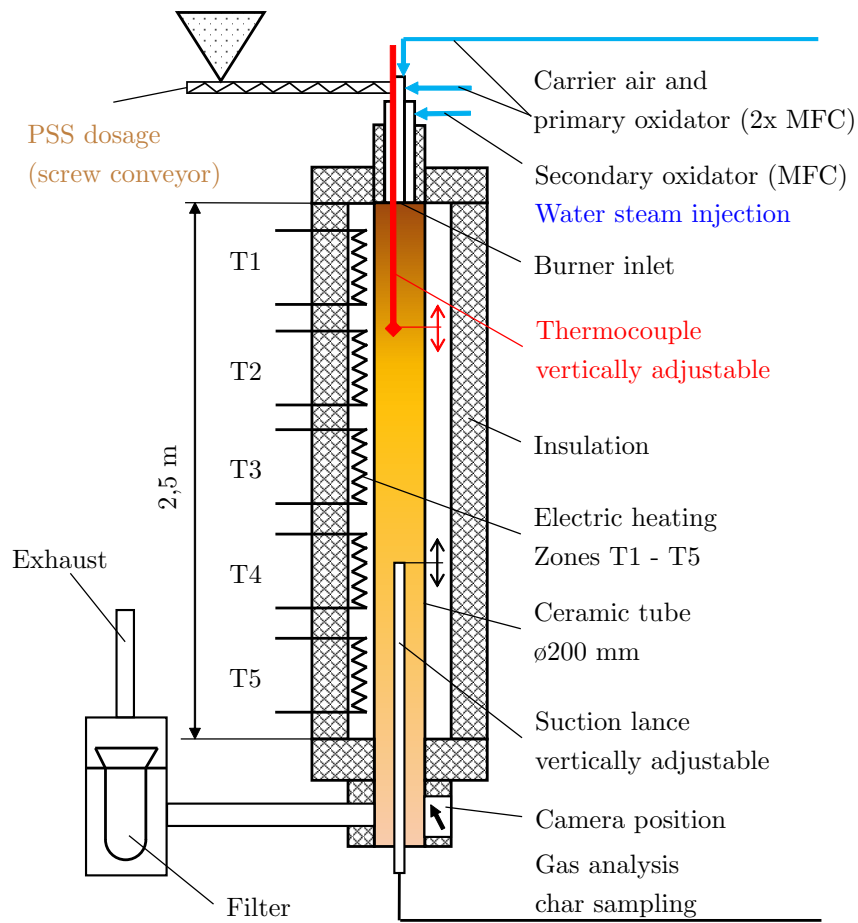


Figure 2: Experimental reactor

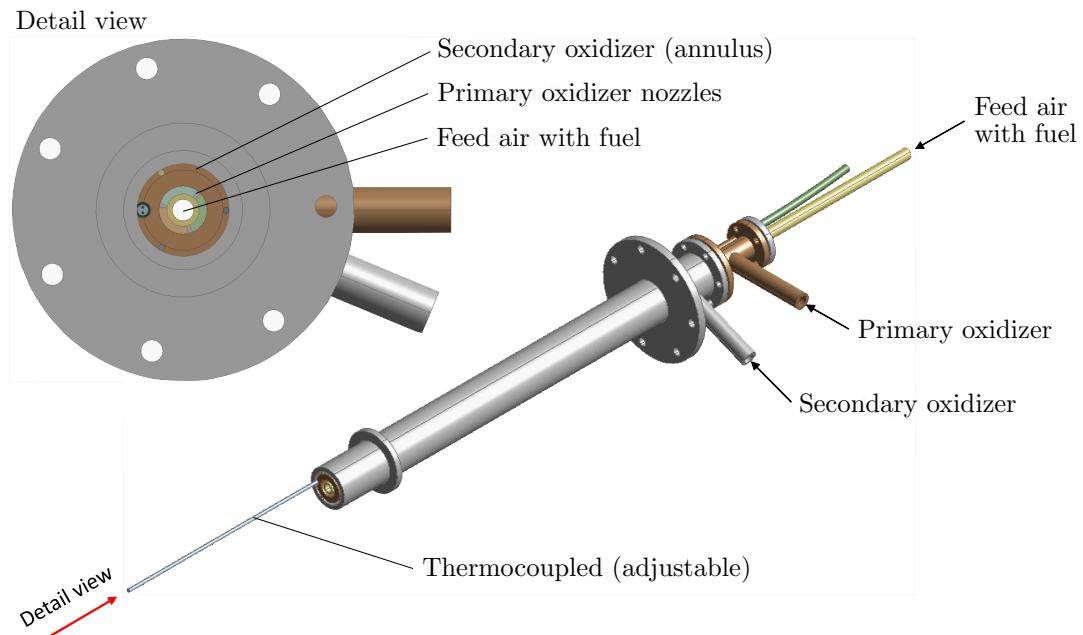


Figure 3: Burner

153 should be noted that the TC measurements have a high level of uncertainty. Nevertheless, they can be used to
 154 assess the combustion behavior close to the inlets better than gas composition measurements. This is because gas
 155 species concentrations were measured from the bottom using the vertically adjustable suction lance. Measurements
 156 close to the burner were not possible because of the excessive buildup of slag on the oil-cooled suction lance, which
 157 led to unsteady data trends. Stable measurement data could only be obtained at distances greater than 0.5 m
 158 from the burner inlets. Before analysis, the dust-free gas stream undergoes conditioning through cooling and water
 159 extraction. Measurement of CO , CO_2 , CH_4 , H_2 , and O_2 is conducted using an Emerson NGA 2000 online gas
 160 analyzer. CO , CO_2 , and CH_4 are detected via NDIR, H_2 through thermal conductivity, and O_2 via paramagnetism.
 161 During the experimental campaign, a total of eight cases were examined. These scenarios were categorized based
 162 on various additive variants and further divided according to the different types of sludge. For reference, this is
 163 illustrated in Figure 4. For each variant, both a combustion case exceeding an excess air ratio (EAR) of one (see
 164 Equation 2) and a substoichiometric combustion case with an EAR below one were selected.

$$\text{EAR} = \frac{\text{amount of oxidizer available}}{\text{stoich. required amount of oxidizer}} \quad (2)$$

165 This latter distinction was made to assess the influence of the oxidizing and reducing atmosphere in the reactor
 166 on the particulate/slag phase. These phenomena will be the focus of further studies. Nevertheless, the developed
 167 CFD model is required to correctly predict the main gas compositions to enable further model developments in this
 168 regard.

169 3. Numerical modeling

170 In this section, the specifics of the computational model are discussed starting with a presentation of the
 171 computational domain, followed by the particle-laden flow- and chemistry modeling. Finally, the relevant boundary
 172 conditions for the considered cases are described. The commercial software *ANSYS Fluent 2024 R1* is used for the
 173 simulations.

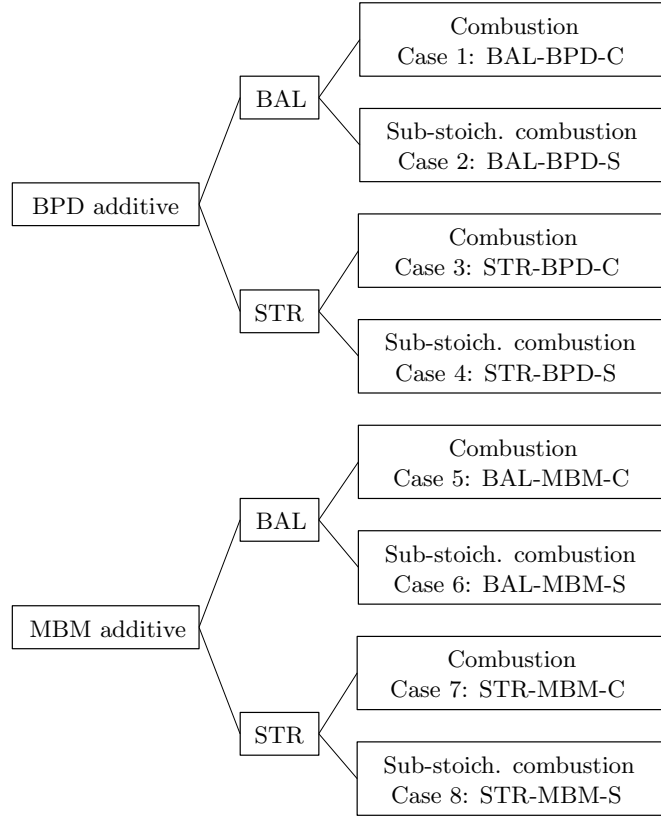


Figure 4: Experimental cases

3.1. Computational domain

The computational domain, as shown in Fig. 5, includes a detailed view of the injection channels of the burner. The fuel enters the main reaction zone through the central fuel inlet together with carrier air, whereas the main part of the oxidizer is injected through three high-velocity nozzles.

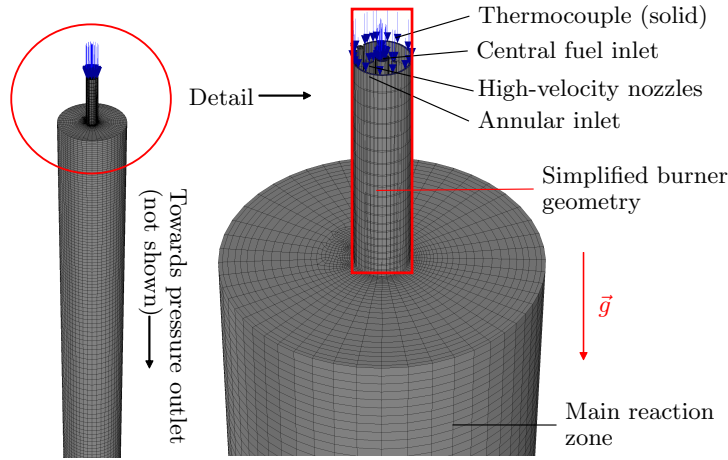


Figure 5: Computational domain, including a detailed view on the inlets

A mesh-independence study was performed in our previous publication [24], in which three different mesh

179 resolutions were tested using a domain with periodic boundary conditions. In the present study, the domain was
180 fully resolved in 3D, leading to a total cell count of 389,260 mainly hexahedral cells.

181 3.2. Particle-laden flow

182 The turbulent flow within the experimental reactor was analyzed by obtaining stable solutions for the Navier-
183 Stokes equations using a pressure-based solver. The incompressible ideal gas law was employed to account for
184 temperature-dependent density. Polynomial approximations were used to incorporate the temperature-dependent
185 specific heat, thermal conductivity, and viscosity of the gas mixture. The applied turbulence model is the k- ω -
186 SST model proposed by Menter [33] and is often recommended for furnace simulations [34–37]. Pressure-velocity
187 coupling is performed via the SIMPLE algorithm. Particles are tracked in a Lagrangian manner employing the
188 Discrete phase model (DPM). The stochastic movement of the particles due to turbulence was considered using the
189 discrete random walk (DRW) model with default constants. Important closure relations are considered in the form
190 of the drag correlation by Haider and Levenspiel [38] and the Nusselt number correlation by Ranz and Marshall
191 [39]. The drag correlation can consider the slight non-spherical particle shape which was determined via DIA to be
192 around $\psi = 0.8$ representing a value for the sphericity defined according to Wadell [40]. The PSD is illustrated in
193 Fig. 1. The particle density of sewage sludge was determined to be 1840 kg/m^3 , BPD: 1550 kg/m^3 and for MBM
194 1410 kg/m^3 was used [41].

195 3.3. Radiation

196 The combination of the discrete ordinates model by Raithby et al. [42] and the Weighted Sum of Gray Gases
197 Model (WSGGM) [43] with standard coefficients [44] was employed to account for gas and black body radiation. An
198 angular discretization of 4x4 per octant was used. This model facilitates particle-radiation interaction, supporting
199 high heating rates. Assumed values for particle, wall, and thermocouple emissivity fall within typical ranges for
200 studies on pulverized fuel combustion and slagging [45–47]. In our study, a value of 0.9 was employed. Wall emissivity
201 was set to 0.9 for slagging considerations, consistent with comparable research [35, 47]. The thermocouple emissivity
202 was estimated at 0.45.

203 3.4. Combustion model

204 When the relevant particle temperature level for drying and devolatilization of 400 K has been reached through
205 radiative and convective heat transfer, the particles undergo a first-order, single kinetic rate reaction [48]. This is a

common approach in the solid fuel combustion modeling [49, 50], although even simpler, constant rate approaches were successfully used [17]. The endothermic effect of the decomposition is not included, since it is small compared to the general heat transfer in a high-heating rate device [51]. Additionally, the surrogate compositions below are trimmed to produce the correct LHV. After the devolatilization process is finished, the subsequent heterogeneous surface reaction of the particles is modeled using a kinetics-/diffusion-limited approach of Baum and Street and Field [52, 53]. The relevant parameters for the particle model are shown in Tab. 3.

Table 3: Particle reaction model parameters

Fuel	Activation energy in $J/kmol$	Pre-exponential factor in s^{-1}	Mass diffusion-limited rate constant	Kinetic limited rate pre-exponential factor	Kinetics-limited rate activation energy in $J/kmol$	Reference
BAL, STR	7.4e+07	312,000	5e-12	0.002	7.9e+07	based on lignite [24, 25, 54]
MBM	1.979e+08	4.78e+14	5e-12	6.7	1.138e+08	[28]
Devolatilization model			Surface reaction model			

The gas phase computation modeling of the system is based on our previous works [24, 25], which is a surrogate-fuel-based method for the combustion calculation of sewage sludge. In Tab. 4, the surrogate fuel compositions obtained by the procedure described in [24] are shown. The compositions contain water vapor H_2O , which is included to account for the water content of the fuel that is expected to evaporate instantly during the rapid heat-up and devolatilization. Similarly, the nitrogen content of the surrogates is used to account for the n-fraction of the elementary analysis. The remaining mole fractions include H_2 , CO , CO_2 , C_3H_6 and C_7H_{16} to take long-chained hydrocarbons into consideration. Tab. 4 also shows the errors introduced by this approach compared to the elementary analysis of the fuel (C/H, C/O ratio) as well as the deviations in stoichiometric oxygen demand and LHV. The composition could not be matched perfectly, but the errors fall within a well-acceptable range. The resulting compositions are also within the range of literature-reported compositions of volatiles emerging from sludge samples [22]. In reality, the true composition of gases originating from particles in entrained flow is difficult to predict, as it also depends on heating rates and temperature levels [55]. Therefore, this surrogate-based approach is considered justified, especially when small particles are considered.

The non-premixed combustion, chemical equilibrium model is applied, using the compositions from Tab. 4 for the fuel species definition and oxygen-enhanced air (30 vol% O_2) for the oxidizer species definition. Non-premixed modeling involves solving transport equations for only two conserved scalars instead of solving equations

Table 4: Surrogate fuel compositions, mole fractions of components

Fuel type	H2O	H2	CO	CO2	C3H6	C7H16	N2	Error Oxidizer	Error LHV	Error C/H	Error C/O
BAL	0.330	0.100	0.080	0.246	0.091	0.075	0.079	-0.05%	+0.96%	-5.85%	-1.16%
STR	0.224	0.100	0.220	0.217	0.013	0.115	0.112	-0.05%	0.00%	-0.44%	+1.65%
MBM	0.049	0.100	0.087	0.087	0.279	0.030	0.148	-0.05%	+0.02%	-1.77%	+0.66%

for individual species. The first one is the mixture fraction f , as defined in Eq. 3, with its transport equation given in Eq. 4 (density-averaged). The second is the mixture fraction variance f'^2 (Transport Eq. 5, $f' = f - \bar{f}$). Species concentrations are derived from predicted mixture fraction fields rather than directly solving equations for each species. The thermochemical calculations are preprocessed and tabulated for lookup in *Fluent*.

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \quad (3)$$

$$\frac{\partial}{\partial t} (\rho \bar{f}) + \nabla \cdot (\rho \vec{v} \bar{f}) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \bar{f} \right) + S_m \quad (4)$$

$$\begin{aligned} & \frac{\partial}{\partial t} (\rho \overline{f'^2}) + \nabla \cdot (\rho \vec{v} \overline{f'^2}) = \\ & \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \overline{f'^2} \right) + C_g \mu_t (\nabla \bar{f})^2 - C_d \rho \frac{\epsilon}{k} \overline{f'^2} \end{aligned} \quad (5)$$

Turbulence-chemistry interactions are addressed using assumed-shape (β -function)-probability density functions (PDF). σ_t is the Prandtl number. Model constants C_g and C_d were left at default values. Since heat transfer through the walls and particle-radiation is included, the non-adiabatic extension of the non-premixed model is used and Eq. 6 has to be solved additionally.

$$\frac{\partial}{\partial t} (\rho \bar{H}) + \nabla \cdot (\rho \vec{v} \bar{H}) = \nabla \cdot \left(\frac{k_t}{c_p} \nabla \bar{H} \right) + S_h \quad (6)$$

As outlined in section 1, a single mixture fraction approach is considered sufficient if only one organic-containing fuel is considered (STR or BAL with BPD). This is because the combustion of sewage sludge is primarily dominated by volatile combustion. In this case, the instantaneous quantities such as mass fractions, densities, and temperatures, $\phi_i = \phi_i(f, H)$, are obtained from three-dimensional lookup tables. This approach introduces an error because it

assumes that the LHV of volatiles and char is the same. However, the already low fixed carbon fraction is determined at low heating rates. In high-heating-rate environments, the entire organic content may evaporate [56]. In contrast, when MBM is considered, a secondary fuel stream, f_{sec} , is introduced to account for the distinct compositions of sewage sludge and MBM. This leads to the use of two mixture fractions, f_{prim} and f_{sec} , respectively. The instantaneous quantities $\phi_i = \phi_i(f_{prim}, p_{sec}, H)$ are then derived from five-dimensional lookup tables, where p_{sec} is the normalized secondary mixture fraction, assumed to be statistically independent from the primary mixture fraction f_{prim} .

3.5. Boundary conditions and other model settings

In total, the simulations in this study involve 8 cases, with different fuel combinations and boundary conditions, respectively. The cases with odd numbers represent a combustion mode at an excess air ratio (EAR) of approximately 1.2, while the even-numbered cases deal with an EAR of approximately 0.8. While the thermal boundary condition of 1300 °C (wall temperature) with an emissivity of $\varepsilon = 0.9$ was kept the same in all cases, the mass flow boundary conditions differ and are listed in Tab. 5. Sludge and additives were premixed and injected as a single mixture during the experiment, whereas in CFD, different injections had to be defined due to the differing chemical and mechanical particle characteristics.

Table 5: Mass flow boundary conditions

Inlet	Massflow in kg/h							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Carrier air	0.829	0.829	0.829	0.829	0.829	0.829	0.829	0.829
High velocity nozzle	2.880	2.880	7.200	4.320	8.415	4.355	7.370	4.320
Annular inlet	3.161	0.851	2.371	1.781	2.396	2.216	3.692	0.828
BAL	2.639	2.639	-	-	1.593	1.593	-	-
STR	-	-	2.885	2.379	-	-	2.379	2.379
MBM	-	-	-	-	1.407	1.407	0.621	0.621
BPD	0.361	0.361	0.115	0.115	-	-	-	-

The convergence of the simulations was evaluated using several criteria. First, the residuals were required to decrease by at least three orders of magnitude for continuity, momentum, and turbulence, and by six orders of magnitude for energy, radiative transfer, and mixture fraction. More critically, the species concentrations at the outlet and the overall velocity field had to stabilize with respect to the iteration count. Additionally, the enthalpy balance had to be fully satisfied, ensuring no energy was missing from the system.

4. Results and discussion

In this section, the results obtained with the simulation model shall be compared to those from the experimental trials. Initially, temperature measurement profiles from the vertically adjustable thermocouple are analyzed. Then, the main gas species concentrations are compared by means of the data from the vertically adjustable suction lance which was inserted from the bottom.

4.1. Temperatures

In Fig. 6, the temperature field results for Case 1 and Case 2, the combustion (left-hand side) and substoichiometric combustion of BAL with BPD are shown. The oxygen mole fraction in the oxidizer was 30vol% in both cases. Following a rapid devolatilization - due to the small-particle sizes and thus high heating rates - of the centrally injected particles, the high-temperature zone (color-coded white) is considered as the consequence of gas phase reactions. It can be seen that the major reaction is finished within a distance of only about 0.5 m from the burner in the combustion case. When the substoichiometric combustion is considered, the flame moves even closer to the burner. This happens because less oxidizer is injected through the burner jets, resulting in reduced momentum flux and thus faster mixing of the injected particles with the hot surrounding atmosphere. The heat release result (total sensible heat transfer rate) is 6853 W for Case 1, which is insignificantly exceeding the fuel power input ($\dot{m} \cdot LHV$) to the system by about 1.5%. This is because as shown in Tab. 4, the LHV of the fuel is captured by the surrogate approach with a small deviation of +0.96%. The remaining difference is negligible and results from the convergence level of the CFD model. The heat release in case 2 is lower because the combustion is substoichiometric. The resulting flue gas has a significant remaining heating value, mainly due to its carbon monoxide and hydrogen content.

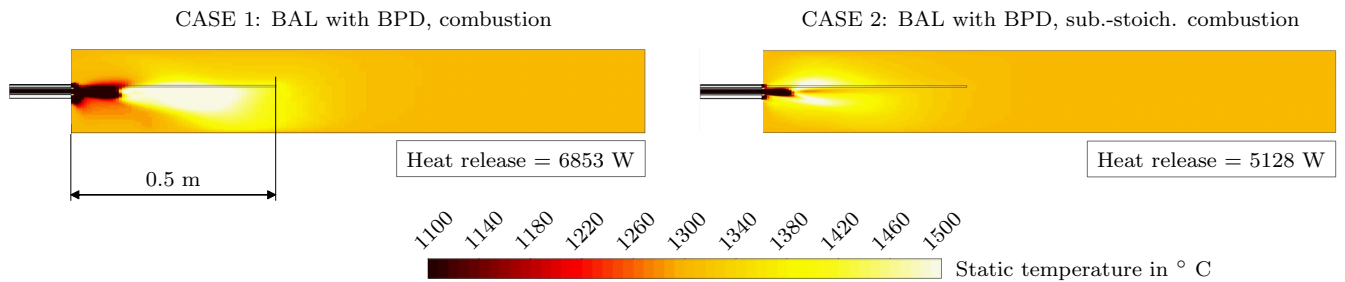
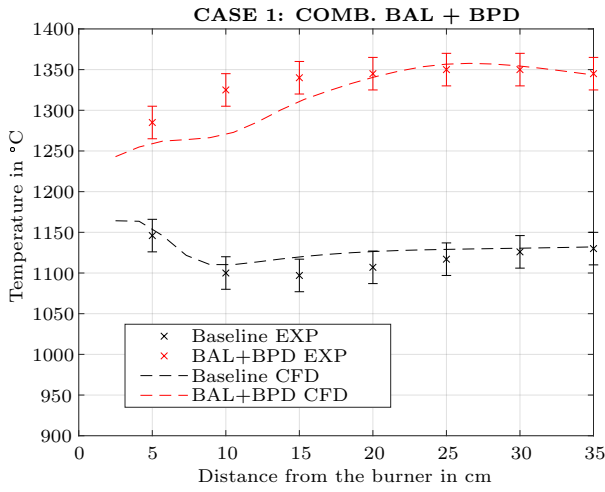


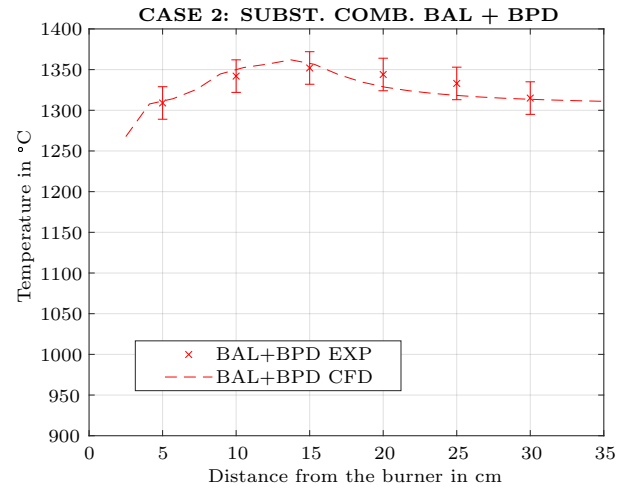
Figure 6: Temperature field result - Left: Combustion case, Right: Substoichiometric combustion case

The first temperature measurement taken by the adjustable thermocouple is compared with the simulation

281 result shown in Fig. 7a. In this figure, the black data represents the baseline temperature obtained prior to
 282 the measurement of case 1. During this stage, oxidizer injections were active, but no fuel has been injected yet.
 283 Therefore, no combustion was taking place. The recorded temperatures, influenced by oxidizer flow and radiation,
 284 exceed 1100 °C at this location, despite the injection of relatively cold air. This temperature rise is attributed to
 285 significant thermal radiation in the region. However, representing the thermocouple as a solid body in the CFD
 286 model yields a satisfactory agreement between measured temperatures and simulation results (illustrated by the
 287 dashed line). The red data represents temperatures after fuel injection started. Despite the strong influence of
 288 radiation from the hot walls, a noticeable temperature jump above 1300 °C is observed near the burner in both
 289 experiment and simulation. This observation confirms the rapid decomposition of particles and subsequent gas
 290 phase reaction near the burner. Analyzing the data for case 2 in Fig. 7b, the close agreement between simulation
 291 and measurement confirms the fast devolatilization and combustion of fuel occurring in close proximity to the
 292 burner, even in cases of substoichiometric combustion.



(a) Combustion of BAL sludge with BPD (including temperature baseline)



(b) Substoichiometric combustion of BAL sludge with BPD

Figure 7: Measured and calculated temperatures within a distance of 35 cm from the burner for the case featuring BAL sludge with BPD additive

293 This is an important insight into the combustion behavior of pulverized sewage sludge. Provided high tempera-
 294 tures in the reactor, ignition of the material is not a concern, as long as the particle sizes are sufficiently small. This
 295 is usually the case in pulverized fuel combustion. The same data was collected for the STR sludge in combination
 296 with BPD in case 3 and case 4. The combustion case in Fig. 8a and the substoichiometric case in Fig. 8b show
 297 very good agreement between experiment and simulation. However, the temperature increase is not that significant

298 compared to case 1 and case 2. This is because the stoichiometric air demand for the combustion of STR is consid-
 299 erably higher, which leads to an increased momentum flux from the inlet. Thereby, the reaction zone is distributed
 300 over a greater distance.

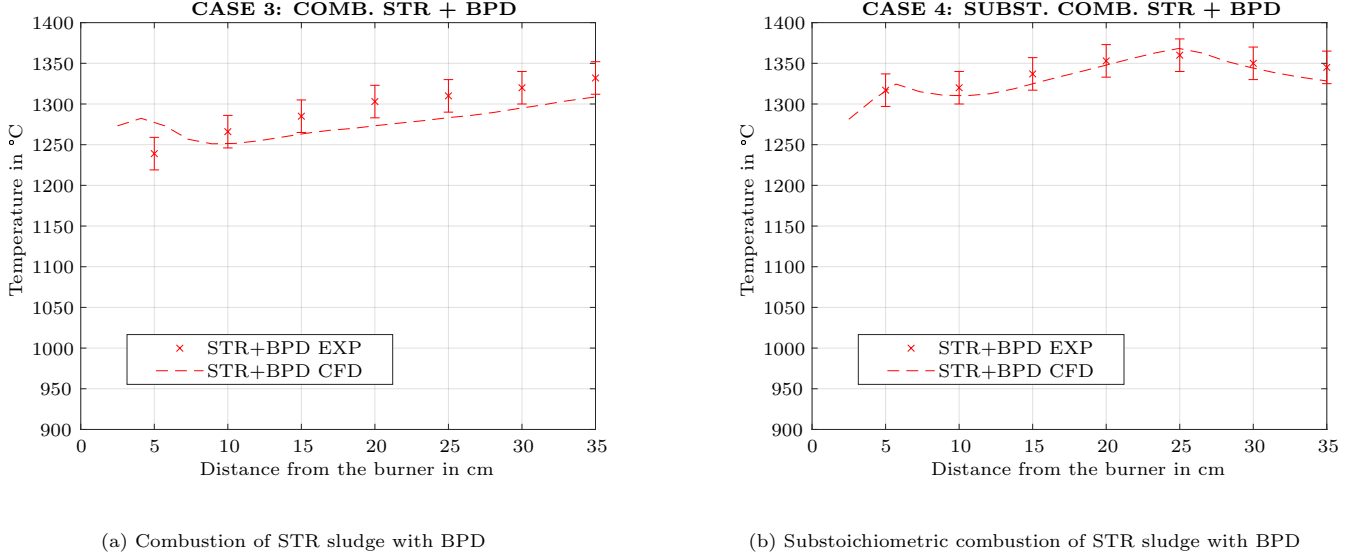
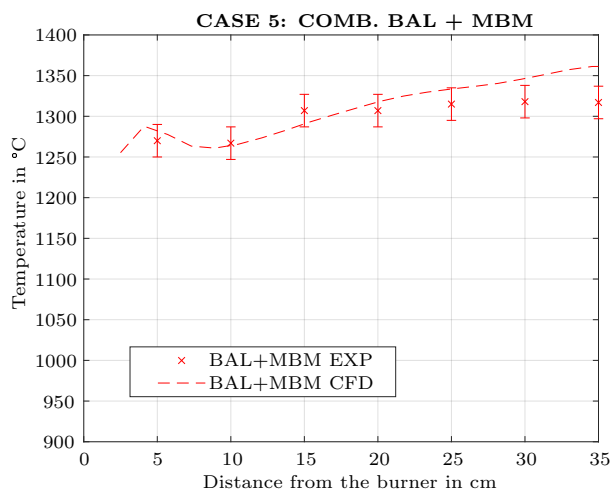


Figure 8: Measured and calculated temperatures within a distance of 35 cm from the burner for the case featuring STR sludge with BPD additive

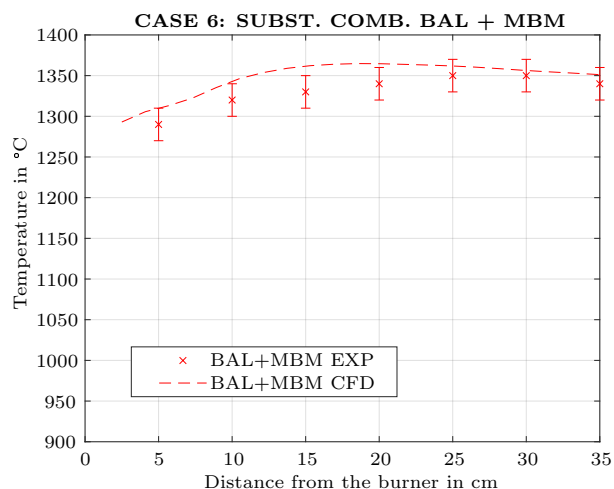
301 Unlike using BPD as an additive, the addition of MBM is expected to have a significant impact on the combustion
 302 behavior. In Fig. 9a, the results for case 5 are shown. While the experimental and CFD calculated temperature
 303 data are close at first, the deviations become larger at a further distance. For case 6 the simulated behavior is
 304 comparable to the substoichiometric combustion in case 2, where a fast temperature increase was calculated close
 305 to the inlets. Experimental data and simulation results show slight discrepancies for all cases, which is due to the
 306 high uncertainties. Nevertheless, major observations from the experiments were also present in the CFD solution.

307 Lastly, the cases 7 and 8 are shown in Fig. 10a and Fig. 10b respectively. Here, a continuous temperature
 308 increase was detected within the considered distance from the inlets. The substoichiometric case shows again that
 309 a large portion of the reaction takes place close to the burner, which was also predicted by the CFD model. As
 310 expected, the measured temperature profiles show the highest values for case 8, where a high heating value fuel is
 311 used. The simulation results were slightly below the measured data.

312 In summary, the following Fig. 11 compares the total heat release per case. It becomes clear that for cases 3 to
 313 8, the expected heat release is very similar in the order of 10 to 12 kW for the combustion cases and from 8 to 9 kW
 314 for the substoichiometric cases. The reason lies in the fact that the total LHV per kg of fuel mixture is similar for
 315 the latter cases and the injected fuel mass flow rate was always 3 kg/h. Only in the case of BAL and BPD (Cases

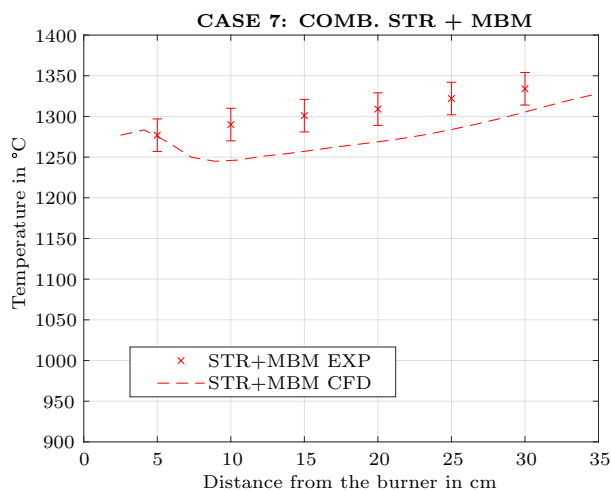


(a) Combustion of BAL sludge with MBM

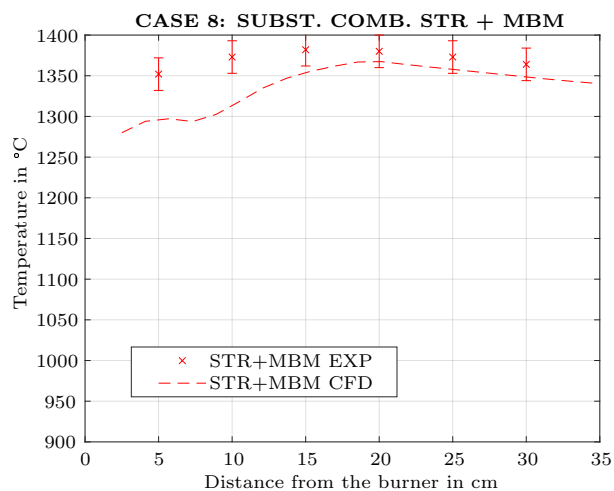


(b) Substoichiometric combustion of BAL sludge with MBM

Figure 9: Measured and calculated temperatures within a distance of 35 cm from the burner for the case featuring BAL sludge with MBM additive



(a) Combustion of STR sludge with MBM



(b) Substoichiometric combustion of STR sludge with MBM

Figure 10: Measured and calculated temperatures within a distance of 35 cm from the burner for the case featuring STR sludge with MBM additive

1 and 2) the heat release is significantly lower.

When adjusting the BAL basicity with BPD, a heat release of 6.8 kW occurs. If MBM is used, its additional heating value increases the heat release to more than 10.8 kW. This +57% increase could substantially impact furnace characteristics, such as temperature distributions and refractory wear. For STR sludge the effect is less pronounced. Firstly, this is because it has a higher heating value, and secondly, because its basicity adjustment requires less BPD or MBM respectively. This is something that should always be considered when adjusting the required basicities of fuel mixtures because significantly differing organic compositions can drastically influence the

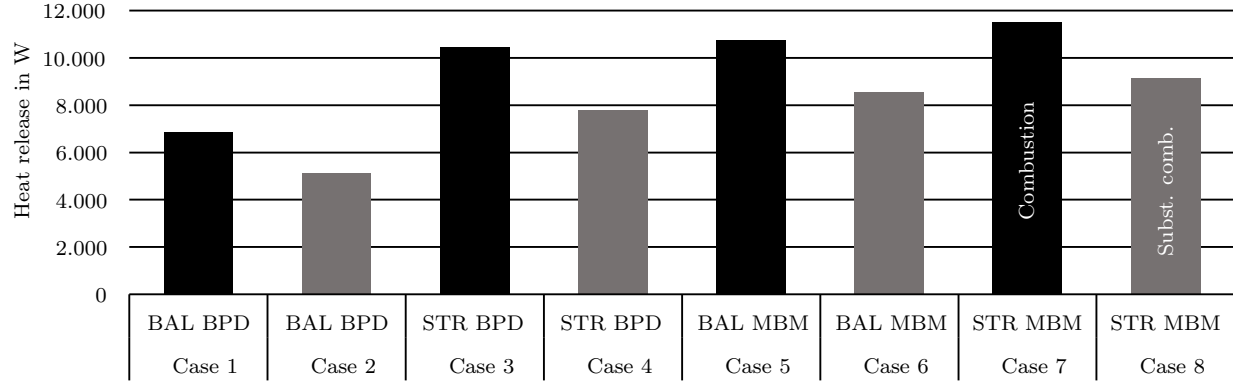


Figure 11: Heat release simulation result per case

rate of heat release and heat transfer.

4.2. Gas phase

In this section, computational and experimental results of the gas phase composition data will be compared. Starting with Fig. 12, which shows the BAL with BPD cases 1 and 2, again shows the rapid consumption of oxygen very close to the burner inlets. Starting at 30vol% of oxygen at the injection, the reaction rapidly reduces the oxygen content to around 5vol% (dry basis). In the substoichiometric case, this decreases, consistent with the chemical equilibrium, nearly to zero.

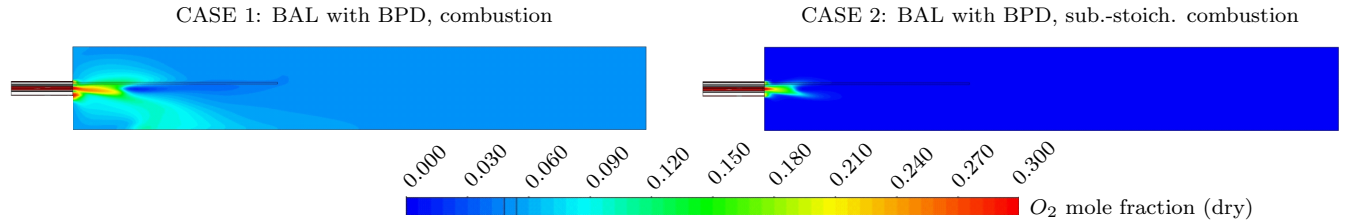


Figure 12: O₂ mole fraction contours

The comparison with measurements in Fig. 13a for case 1 confirms the CFD model's results. The CO₂ mole fraction is determined to be about 22.5vol% (dry basis). Again, the data reveals that the major reaction is already finished at a distance of 0.5 m from the burner, where the first measurement point was taken. However, it was not possible to obtain a stable measurement closer than the previously mentioned 0.5 m because instant obstruction of the suction lance did not allow for stable measurements in this region. In case 2, the CO and CO₂ mole fraction were accurately predicted. This is significant because the CO/CO₂ is important as a measure for the reducing

characteristics of an atmosphere. In addition to affecting the recovery rates of valuable ingredients from the ashes [57], this may also influence the viscosity of the slag [58]. Knowledge of this is crucial to improve the phosphorus yield from the waste combustion process. Based on this computationally inexpensive CFD modeling concept, the slag behavior should be the subject of further studies.

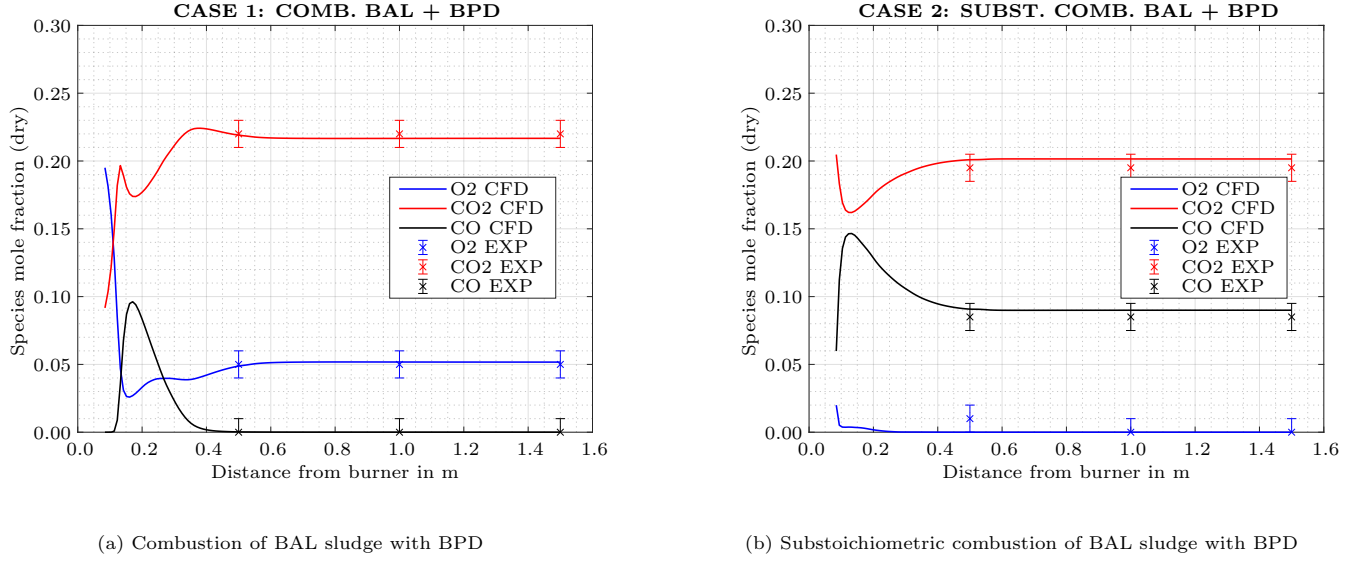
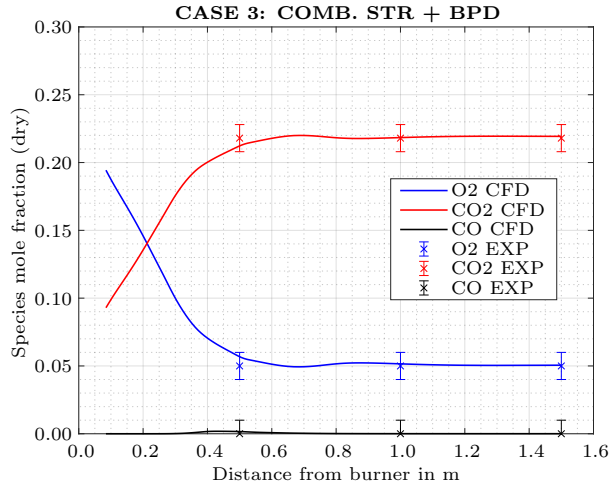


Figure 13: Measured and calculated species mole fractions within a distance of 1.5 m from the burner for the case featuring BAL sludge with BPD additive

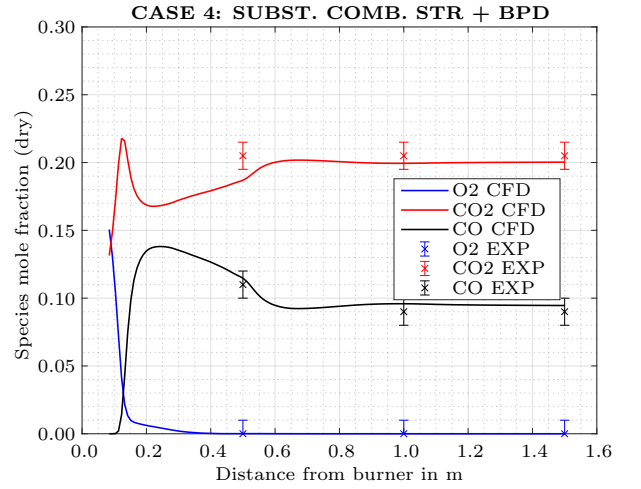
Cases 3 and 4 (STR with BPD) are shown in Fig. 14a with very similar values to cases 1 and 2. This is due to the similarity of the sludge samples. Compared to BAL sludge, the burnout is slower as indicated by the smaller gradients in the species profiles. The reason most likely lies in the STR-PSD that contains larger fractions compared to that of the BAL sludge. Nevertheless, concentrations barely change after a distance of 0.5 m from the burner, which confirms the rapid reaction behavior of the sewage sludge.

Fig. 15a shows the interesting feature of a linear-appearing trend in the CO_2 and O_2 measurement results, which was also predicted by the CFD model. With an increasing distance from the burner inlets, the O_2 fraction decreased, while the CO_2 fraction increased. This is a clear indication of a reduced burnout rate. Because this behavior was not detected during the measurements with BPD, neither with BAL nor STR sludge, this must clearly be attributed to the MBM fractions in the fuel mixture. Fig. 15b shows an inverse trend in that the CO_2 fraction decreases towards the outlet, while the CO fraction did show an increasing trend in both CFD and experimental data. This pattern is expected under substoichiometric conditions, as the ongoing conversion of particles releases volatiles over a longer distance, shifting the chemical equilibrium towards CO .

The reason for both phenomena is mainly the large particle size of the MBM compared to the sludge probes

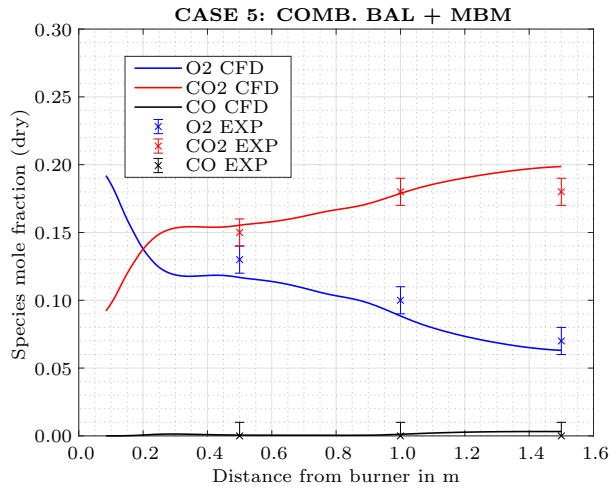


(a) Combustion of STR sludge with BPD

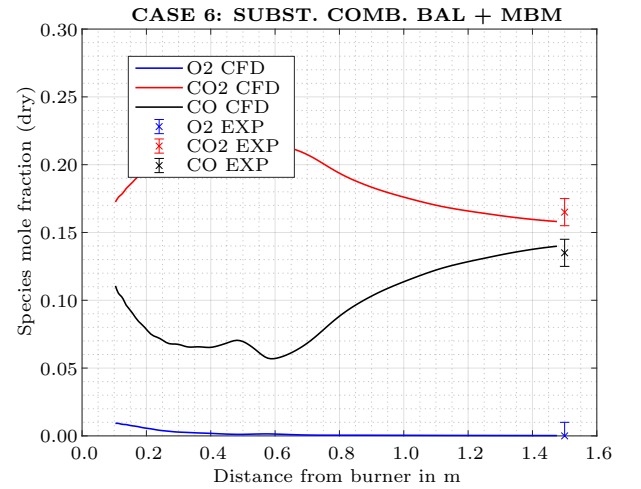


(b) Substoichiometric combustion of STR sludge with BPD

Figure 14: Measured and calculated species mole fractions within a distance of 1.5 m from the burner for the case featuring STR sludge with BPD additive



(a) Combustion of BAL sludge with MBM



(b) Substoichiometric combustion of BAL sludge with MBM

Figure 15: Measured and calculated species mole fractions within a distance of 1.5 m from the burner for the case featuring BAL sludge with MBM additive

(see Fig. 1). The MBM particles do not show instant devolatilization like the sludge particles but instead display a prolonged burnout. While in case 5, this can be attributed to continuing char oxidation with continuing residence time, it is a gasification process enabled by the carbon dioxide CO_2 -containing atmosphere in the reactor, most probably due to the Boudouard reaction Eq. 7, but the H_2O fraction may also play a role during gasification.



Cases 7 and 8 with STR and MBM show very similar trends. The measured curves appear flatter than in cases 5 and 6 (BAL with MBM) because the fraction of MBM in the fuel of 20.7% is lower for STR sludge. For BAL sludge, the fraction of MBM in the mixture is 46.9%, leading to a more pronounced effect of the slower burnout. In total, the gas phase compositions could be well predicted by the CFD model. Close to the burner, the small particle fractions up to 100 μm (BAL, STR, smaller-sized fractions of MBM) react very fast, justifying the fast-chemistry modeling approach. For large particle sizes (up to 1 mm for the largest MBM particles), the char oxidation and gasification reaction dominates, which was captured by the CFD model with sufficient accuracy.

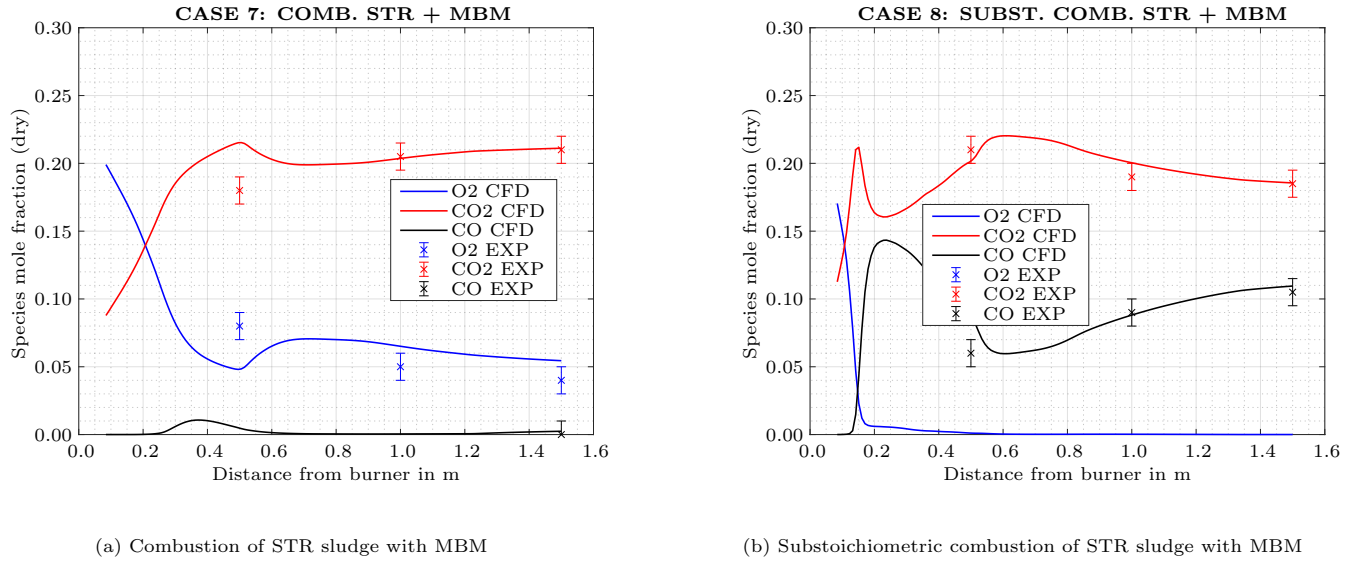


Figure 16: Measured and calculated species mole fractions within a distance of 1.5 m from the burner for the case featuring STR sludge with MBM additive

In summary, the results demonstrated that temperature and gas species concentrations obtained from simulations were in strong agreement with experimental data across all cases. The addition of MBM influenced the combustion behavior considerably, slowing burnout rates and altering the gas phase compositions due to its larger particle sizes. The heat release was found to vary depending on the fuel mixtures, with BAL and BPD exhibiting lower heat release compared to the other combinations.

5. Conclusions and outlook

This study investigated the combustion behavior of sewage sludge with two different additives for basicity adjustment - cement bypass dust and meat and bone meal - focusing on their effects on temperature profiles, gas phase composition, and overall heat release. The comparison between experimental data and CFD simulation results has shown and confirmed major differences between the two additives. Firstly, the addition of MBM changed the

total energy content of the mixture with BAL sludge significantly, causing a 57% increase in heat release in the furnace. For STR sludge, this effect was less pronounced. Secondly, the addition of MBM, with its larger particle sizes, resulted in slower burnout rates. BPD, on the other hand, clearly had a more limited impact on combustion behavior regardless of the sludge type.

The CFD model accurately captured major phenomena like temperature- and gas species profiles and demonstrated its potential as an efficient tool for the scale-up process. Possible topics for future research are the impact of the different fuel-additive mixtures on phosphorus recovery rates and the behavior and impact of molten slag in the entrained flow furnaces, a major issue in the combustion of sewage sludge-containing mixtures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958267. 

Disclaimer

This publication reflects only the authors' views, and the European Health and Digital Executive Agency (HaDEA) and the European Commission are not responsible for any use that may be made of the information it contains.

References

- [1] A. Bianchini, L. Bonfiglioli, M. Pellegrini, C. Saccani, Sewage sludge management in europe: a critical analysis of data quality, *International Journal of Environment and Waste Management* 18 (3) (2016) 226. doi:10.1504/IJEWM.2016.10001645.
- [2] M. Atienza-Martínez, G. Gea, J. Arauzo, S. Kersten, A. Kootstra, Phosphorus recovery from sewage sludge char ash, *Biomass and Bioenergy* 65 (2014) 42–50. doi:10.1016/j.biombioe.2014.03.058.
- [3] European Commission, Report on critical raw materials and the circular economy, Brussels, 2018. URL <https://bit.ly/30PtNuz>
- [4] European Commission, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability, Brussels, 2020. URL <https://ec.europa.eu/docsroom/documents/42849>
- [5] M. Cyr, M. Coutand, P. Clastres, Technological and environmental behavior of sewage sludge ash (ssa) in cement-based materials, *Cement and Concrete Research* 37 (8) (2007) 1278–1289. doi:10.1016/j.cemconres.2007.04.003.
- [6] S. Donatello, D. Tong, C. R. Cheeseman, Production of technical grade phosphoric acid from incinerator sewage sludge ash (issa), *Waste management (New York, N.Y.)* 30 (8-9) (2010) 1634–1642. doi:10.1016/j.wasman.2010.04.009.
- [7] P. Staroń, Z. Kowalski, A. Staroń, J. Seidlerová, M. Banach, Residues from the thermal conversion of waste from the meat industry as a source of valuable macro- and micronutrients, *Waste management (New York, N.Y.)* 49 (2016) 337–345. doi:10.1016/j.wasman.2016.01.018.
- [8] I. Gulyurtlu, D. Boavida, P. Abelha, M. H. Lopes, I. Cabrita, Co-combustion of coal and meat and bone meal, *Fuel* 84 (17) (2005) 2137–2148. doi:10.1016/j.fuel.2005.04.024.
- [9] L. Fryda, K. Panopoulos, P. Vourliotis, E. Pavlidou, E. Kakaras, Experimental investigation of fluidised bed co-combustion of meat and bone meal with coals and olive bagasse, *Fuel* 85 (12-13) (2006) 1685–1699. doi:10.1016/j.fuel.2006.01.020.

- 418 [10] O. Senneca, Characterisation of meat and bone mill for coal co-firing, *Fuel* 87 (15-16) (2008) 3262–3270.
419 doi:10.1016/j.fuel.2008.04.012.
- 420 [11] E. Cascarosa, L. Gasco, G. Gea, J. L. Sánchez, J. Arauzo, Co-gasification of meat and bone meal with coal in
421 a fluidised bed reactor, *Fuel* 90 (8) (2011) 2798–2807. doi:10.1016/j.fuel.2011.04.005.
- 422 [12] M. Kantorek, K. Jesionek, S. Polesek-Karczewska, P. Ziolkowski, J. Badur, Thermal utilization of meat and
423 bone meals. performance analysis in terms of drying process, pyrolysis and kinetics of volatiles combustion,
424 *Fuel* 254 (2019) 115548. doi:10.1016/j.fuel.2019.05.131.
- 425 [13] E. Cascarosa, A. Boldrin, T. Astrup, Pyrolysis and gasification of meat-and-bone-meal: energy balance and ghg
426 accounting, *Waste management (New York, N.Y.)* 33 (11) (2013) 2501–2508. doi:10.1016/j.wasman.2013.07.014.
- 427 [14] S. M. El-Haggar, *Sustainable Industrial Design and Waste Management: Cradle-to-cradle for Sustainable*
428 *Development*, 2007. doi:10.1016/B978-0-12-373623-9.X5000-X.
- 429 [15] N. Gao, K. Kamran, C. Quan, P. T. Williams, Thermochemical conversion of sewage sludge: A critical review,
430 *Progress in Energy and Combustion Science* 79 (2020) 100843. doi:10.1016/j.pecs.2020.100843.
- 431 [16] H. Zhang, K. Okuyama, S. Higuchi, G. Soon, G. Lisak, A. W.-K. Law, Cfd-dem simulations of municipal solid
432 waste gasification in a pilot-scale direct-melting furnace, *Waste management (New York, N.Y.)* 162 (2023)
433 43–54. doi:10.1016/j.wasman.2023.03.008.
- 434 [17] J. Hercog, R. Lewtak, B. Glot, P. Józwiak, G. Nehring, V. D. Tavares, A. M. Nunes, D. Gaspar, Pi-
435 lot testing and numerical simulations of the multifuel burner for the cement kiln, *Fuel* 342 (2023) 127801.
436 doi:10.1016/j.fuel.2023.127801.
- 437 [18] Y. Wang, L. Yan, Cfd based combustion model for sewage sludge gasification in a fluidized bed, *Frontiers of*
438 *Chemical Engineering in China* 3 (2) (2009) 138–145. doi:10.1007/s11705-009-0050-7.
- 439 [19] J. Werther, T. Ogada, Sewage sludge combustion, *Progress in Energy and Combustion Science* (25) (1999)
440 55–116. doi:10.1016/S0360-1285(98)00020-3.
- 441 [20] T. Ogada, J. Werther, Combustion characteristics of wet sludge in a fluidized bed, *Fuel* 5 (75) (1996).
442 doi:10.1016/0016-2361(95)00280-4.

- [21] H. Cui, Y. Ninomiya, M. Masui, H. Mizukoshi, T. Sakano, C. Kanaoka, Fundamental behaviors in combustion of raw sewage sludge, *Energy & Fuels* 20 (1) (2006) 77–83. doi:10.1021/ef050188d.
- [22] A. Žnidarčič, T. Seljak, T. Katrašnik, Surrogate model for improved simulations of small-scale sludge incineration plants, *Fuel* 280 (2020) 118422. doi:10.1016/j.fuel.2020.118422.
- [23] A. Žnidarčič, T. Katrašnik, I. G. Zsély, T. Nagy, T. Seljak, Sewage sludge combustion model with reduced chemical kinetics mechanisms, *Energy Conversion and Management* 236 (2021) 114073. doi:10.1016/j.enconman.2021.114073.
- [24] B. Ortner, C. Schmidberger, H. Gerhardtter, R. Prieler, H. Schröttner, C. Hochenauer, Computationally inexpensive cfd approach for the combustion of sewage sludge powder, including the consideration of water content and limestone additive variations, *Energies* 16 (4) (2023) 1798. doi:10.3390/en16041798.
- [25] B. Ortner, C. Schmidberger, H. Gerhardtter, R. Prieler, H. Schröttner, C. Hochenauer, Application of computationally inexpensive cfd model in steady-state and transient simulations of pulverized sewage sludge combustion, *Advanced Powder Technology* 34 (12) (2023) 104260. doi:10.1016/j.appt.2023.104260.
- [26] J. M. Heikkinen, B. Venneker, G. Di Nola, W. de Jong, H. Spliethoff, Cfd simulation and experimental validation of co-combustion of chicken litter and mbm with pulverized coal in a flow reactor, *Fuel Processing Technology* 89 (9) (2008) 874–889. doi:10.1016/j.fuproc.2008.02.004.
- [27] W. H. K. Ariyaratne, A. Malagalage, M. C. Melaaen, L.-A. Tokheim, Cfd modelling of meat and bone meal combustion in a cement rotary kiln – investigation of fuel particle size and fuel feeding position impacts, *Chemical Engineering Science* 123 (2015) 596–608. doi:10.1016/j.ces.2014.10.048.
- [28] T. J. Taha, A. F. Stam, K. Stam, G. Brem, Cfd modeling of ash deposition for co-combustion of mbm with coal in a tangentially fired utility boiler, *Fuel Processing Technology* 114 (2013) 126–134. doi:10.1016/j.fuproc.2013.03.042.
- [29] M. Bai, L. Zhang, Y. Zhao, S. Sun, S. Du, P. Qiu, W. Zhang, D. Feng, Numerical simulation on the deposition characteristics of mswi fly ash particles in a cyclone furnace, *Waste management (New York, N.Y.)* 161 (2023) 203–212. doi:10.1016/j.wasman.2023.03.004.

- [30] C. Schmidberger, M. Schmid, K. Kopper, Flashphos: The complete thermochemical recycling of sewage sludge: Conceptual engineering - public deliverable 4.1 (2021).
URL <https://flashphos-project.eu>
- [31] G. Häggström, T. K. Hannl, P. Holmgren, M. Broström, N. Skoglund, M. Öhman, Fate of phosphorus in pulverized fuel co-combustion of sewage sludge and agricultural residues, *Fuel* 335 (2023) 127059. doi:10.1016/j.fuel.2022.127059.
- [32] E. O. Lidman Olsson, P. Glarborg, K. Dam-Johansen, H. Wu, Review of phosphorus chemistry in the thermal conversion of biomass: Progress and perspectives, *Energy & Fuels* 37 (10) (2023) 6907–6998. doi:10.1021/acs.energyfuels.2c04048.
- [33] F. R. Menter, Zonal two equation k-w turbulence models for aerodynamic flows, AIAA-93-2906 (1993). doi:10.2514/6.1993-2906.
- [34] D. Christ, The effect of char kinetics on the combustion of pulverized coal under oxyfuel conditions: Zugl.: Aachen, Techn. Hochsch., Diss., 2013, 1st Edition, Sierke, Göttingen, 2013.
- [35] K. M. Jønck, CFD Modelling of Melting Cyclones for Stone Wool Production, 2021.
- [36] M. Kumar, A. F. Ghoniem, Multiphysics simulations of entrained flow gasification. part ii: Constructing and validating the overall model, *Energy & Fuels* 26 (1) (2012) 464–479. doi:10.1021/ef2008858.
- [37] M. Kumar, A. F. Ghoniem, Multiphysics simulations of entrained flow gasification. part i: Validating the nonreacting flow solver and the particle turbulent dispersion model, *Energy & Fuels* 26 (1) (2012) 451–463. doi:10.1021/ef200884j.
- [38] A. Haider, O. Levenspiel, Drag coefficient and terminal velocity of spherical and nonspherical particles, *Powder Technology* 58 (1988) 63–70. doi:10.1016/0032-5910(89)80008-7.
- [39] W. E. Ranz, W. Marshall, Evaporation from drops, *Chemical Engineering Progress* 48 (3) (1952) 141–146.
- [40] H. A. Wadell, Volume, shape and roundness of rock particles, *The Journal of Geology* 40 (5) (1932) 443–541. doi:10.1086/623964.

- [41] R. A. Garcia, K. A. Rosentrater, R. A. Flores, Characteristics of north american meat and bone meal relevant to the development of non-feed applications, *Applied Engineering in Agriculture* 22 (5) (2006) 729–736. doi:10.13031/2013.21989.
- [42] G. D. Raithby, E. H. Chui, A finite-volume method for predicting a radiant heat transfer in enclosures with participating media, *J. Heat. Transf* 112 (1990) 415–423. doi:10.1115/1.2910394.
- [43] H. C. Hottel, A. F. Sarofim, Radiative transfer, McGraw-Hill Book Company (1967). doi:10.1002/aic.690150504.
- [44] T. F. Smith, F. Shen, N. Friedman, Evaluation of coefficients for the weighted sum of gray gases mode, *J. Heat Transfer* 104 (1982) 602–608. doi:10.1115/1.3245174.
- [45] S. Akaotsu, Y. Matsushita, H. Aoki, W. Malalasekera, Application of flamelet/progress-variable approach to the large eddy simulation of a turbulent jet flame of pulverized coals, *Advanced Powder Technology* 31 (10) (2020) 4253–4274. doi:10.1016/j.appt.2020.09.005.
- [46] H. Gerhardter, M. Knoll, R. Prieler, M. Landfahrer, M. Mühlböck, P. Tomazic, C. Hochenauer, Determining the heating characteristics of non-spherical particles in combusting flows, *Applied Thermal Engineering* 151 (2019) 124–133. doi:10.1016/j.applthermaleng.2019.02.006.
- [47] H. Gerhardter, M. Knoll, J. Raic, R. Prieler, M. Landfahrer, C. Hochenauer, P. Tomazic, H. Schroettner, In-flame spheroid formation from non-spherical slag particles – a numerical and experimental study, *International Journal of Heat and Mass Transfer* 151 (2020) 119412. doi:10.1016/j.ijheatmasstransfer.2020.119412.
- [48] S. Badzioch, P. G. W. Hawksley, Kinetics of thermal decomposition of pulverized coal particles, *Industrial & Engineering Chemistry Process Design and Development* 9 (4) (1970) 521–530. doi:10.1021/i260036a005.
- [49] J. Mularski, H. Pawlak-Kruczek, N. Modliński, A review of recent studies of the cfd modelling of coal gasification in entrained flow gasifiers, covering devolatilization, gas-phase reactions, surface reactions, models and kinetics, *Fuel* 271 (2020) 117620. doi:10.1016/j.fuel.2020.117620.
- [50] J. Mularski, Modliński N., Entrained flow coal gasification process simulation with the emphasis on empirical devolatilization models optimization procedure, *Applied Thermal Engineering* 175 (2020) 115401. doi:10.1016/j.applthermaleng.2020.115401.

- 518 [51] N. P. Niemelä, H. Tolvanen, T. Saarinen, A. Leppänen, T. Joronen, Cfd based reactivity parameter determi-
519 nation for biomass particles of multiple size ranges in high heating rate devolatilization, *Energy* 128 (2017)
520 676–687. doi:10.1016/j.energy.2017.04.023.
- 521 [52] M. M. Baum, P. J. Street, Predicting the combustion behavior of coal particles, *Combust. Sci. Tech.* 3 (5)
522 (1971) 231–243.
- 523 [53] M. A. Field, Rate of combustion of size-graded fractions of char from a low rank coal between 1200 k-2000 k,
524 *Combustion and Flame* 13 (1969) 237–252.
- 525 [54] A. I. ANSYS Fluent, Theory Guide Release 2020 R2, Canonsburg, PA, USA, 2020.
- 526 [55] D. F. Fletcher, B. S. Haynes, F. C. Christo, S. D. Joseph, A cfd based combustion model of an entrained flow
527 biomass gasifier, *Applied Mathematical Modelling* 24 (3) (2000) 165–182. doi:10.1016/S0307-904X(99)00025-6.
- 528 [56] S. Arnout, A. Kotze, E. Nagels, Y. Cryns, D. Messina, Flashphos: Elemental phosphorus recovery from sewage
529 sludge - raw material thermal behaviour, *Prceedings of the EMC* (2023).
- 530 [57] K. Morita, N. Sano, 3 - phase diagrams, phase transformations, and the prediction of metal properties, Wood-
531 head Publishing Series in Metals and Surface Engineering (2005) 82–108.
- 532 [58] S. Vargas, F. J. Frandsen, K. Dam-Johansen, Rheological properties of high-temperature melts of coal ashes
533 and other silicates, *Progress in Energy and Combustion Science* 27 (3) (2001) 237–429. doi:10.1016/S0360-
534 1285(00)00023-X.