

CHARACTERIZATION OF THE COMBUSTION BEHAVIOR OF “DMC Fuel™”

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ABSTRACT

The combustion of biomass is regarded as a sustainable, CO₂ - neutral energy source worldwide. In Germany, it has gained particular importance due to the recent change in energy policy, which has led to an increase of renewable energy installations like pellet stoves for domestic heating¹⁻³ and biomass thermal power plants at the industrial and utility scale.⁴⁻⁶ Consequently, wood imports and exports between European countries have increased substantially and excess demand is satisfied primarily by imports from the US and Canada.

In 2014 about 4.4 million tons of wood pellets were imported into the EU, mainly to the UK.⁷⁻¹⁰ The delivered costs for home use wood pellets is about 0.02 €/MJ or 320 €/t.^{9,11} In comparison, imported bulk coal for industrial/utility use is one tenth of that price.

The shipping and the storage of biomass fuels however, are associated with certain hazardous risks as well. These include the spontaneous emission of CO from dry wood chips and from wood pellets,^{9,12,13} as well as spontaneous ignition of wet wood chips, which requires costly security measures.^{9,12,14}

To reduce the costs for the production of biogenic fuel, TMTS Associates, Inc. developed DMC Fuel™ (dry micro chip fuel). This fuel requires only half the electric power and half the capital equipment to manufacture as compared to pellets. Moreover, in comparison to conventional wood chips and wood pellets, its propensity to emit CO is significantly reduced.⁹

At KIT, the combustion process of solid fuels is investigated in a fixed bed reactor and characteristic parameters are derived for the quantitative description of solid fuel combustion. The experimentally determined characteristic numbers allow for a quantitative comparison of the behavior of different fuels and they are useful to estimate the combustion behavior in grate firings.¹⁵⁻¹⁷ The experimental studies are carried out in a fixed bed reactor (KLEAA) at the Institute for Technical Chemistry (ITC) at KIT. In this paper, two standardized fuels (wood pellets and wood chips) and the DMC Fuel™ are investigated. The goal was to assess the applicability of the novel fuel to home pellet stoves and industrial grate firings.

INTRODUCTION

Due to the worldwide efforts for sustainable electricity and heat generation the consumption of regenerative fuels rises continuously.^{4,18,19} This is particularly true in Germany because of its recent change of energy policy. In this context, the safe long-term storage of solid fuels is of high importance. This holds for both static on-site silos as well as for mobile containers during transportation. The major problem is the spontaneous release of carbon monoxide (CO) from piled up dry wood particles and wood pellets which may cause serious hazards to installations and personnel and hazards from combustible dust generation in handling of bulk wood pellets.^{9,12-14} In order to avoid this problem, TMTS Associates developed and tested a new form of the regenerative fuel termed DMC FuelTM. Production is via a new generation of in-forest and in-plant micro chip-pers that are widely available from forestry equipment manufacturers. These allow the production of a range of micro chip sizes, followed by drying to about 10 % moisture content using traditional rotary dryers. The spontaneous CO release from this DMC FuelTM fuel was below detection in preliminary tests, and the production costs of this fuel are substantially lower than those of customary wood pellets. The manufacturing of the fuel requires only half the energy and capital requirements compared to conventional procedures.⁹ In addition to lower CO emissions expected of this fuel as compared to wood pellets, it can be stored under simple ventilated roofed storage to keep it out of the rain, rather than in silos used for pellet storage, which can build up CO.^{9,12,13}

The characterization and comparison of different fuels requires a comprehensive knowledge of their properties and combustion behavior. The physical and chemical properties and the calorific values of the fuels were determined by standard analytical methods. In this paper, the combustion behavior of DMC FuelTM is investigated in the fixed bed reactor KLEAA³⁻⁵ of ITC at KIT and compared to the combustion behavior of conventional wood chips and wood pellets. To describe the combustion behavior, the following characteristic parameters are measured at the KLEAA experimentally: The reaction front velocity u_{RF} , the ignition rate IR and the mass conversion rate MCR. The characteristic numbers are scale independent and can be used to predict the combustion behavior in industrial and utility (grate) firings.^{15-17,20} In addition, the overbed gas compositions are measured and compared. The results are used to assess the feasibility of substituting the conventional fuels with the newly developed fuel.

In the following section, the experimental set-up and the experimental procedure are described as well as the data evaluation to obtain the characteristic numbers. Finally, the results are reported and discussed.

EXPERIMENTAL INVESTIGATIONS

Materials and Analysis

**Figure 1: Fuels investigated
wood chips, wood pellets, DMC Fuel™ (from left to right)**



Figure 1 shows the three fuels investigated. Obviously, they have different size distributions and surface properties. The DMC Fuel™ particles are slightly smaller than the wood chips. The particle size distributions, determined according DIN 66165-1²¹, are shown in Figure 7, with D_{p50} being 6, 5 and 2 mm for wood chips, DMC Fuel™ and wood pellets, respectively.

The materials were tested by elementary, proximate, calorific value and trace element analysis in order to compare the compositions of the feedstocks with each other. Subsequently, they were examined in the test facility KLEAA regarding the combustion behavior. The experimental setup and the measurement method are explained in the following sections.

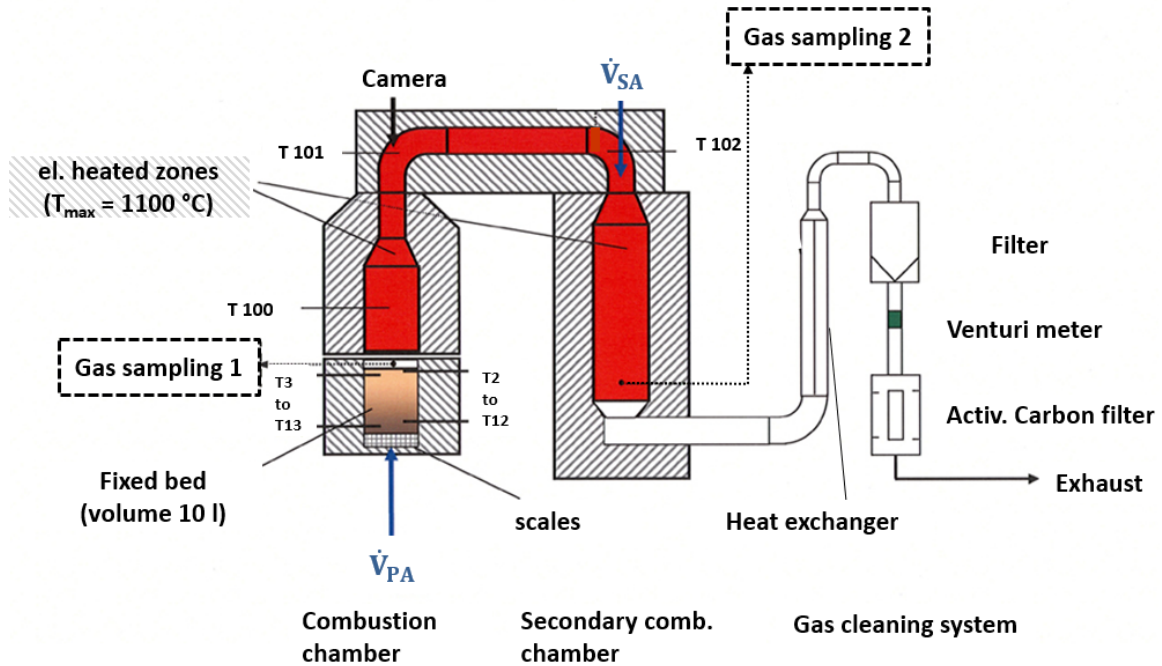
Plant Design

The KLEAA fixed bed reactor unit comprises three main components:

The combustion chamber with a fixed bed and a heated furnace, the post combustion chamber and the flue gas cleaning system which consists of a heat exchanger, a bag filter and a carbon adsorber. The fuel bed has a volume of 10 liters. Compared to thermogravimetric methods, where samples are in the mass range from mg to g, the fixed bed reactor KLEAA is suited to investigate several kg of fuel samples. The furnace and the post combustion chamber can be heated electrically up to a maximum temperature of 1100 °C. Primary air is supplied from the bottom through a sintered metal plate and can be pre-heated up to a maximum temperature of 300 °C. The major components of the facility are represented schematically in Figure 2. A more detailed description of the facility is available elsewhere.^{17,20}

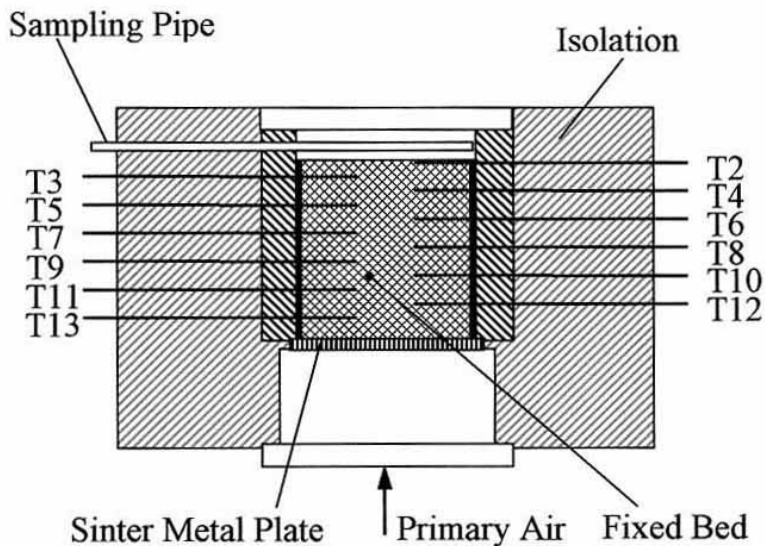
The solid fuel is ignited by radiant heat from the furnace and burns down in opposite direction to the primary air flow, i.e., from top to bottom. Gas samples are taken at two different locations (see Figure 2). The concentrations of CO₂, CO, organic carbon (C_{org}), H₂ and O₂ are determined above the fuel bed. At the outlet of the post combustion chamber CO₂, CO, H₂O and O₂ are determined and the trace gases NO, NO_x, N₂O, SO₂ and HCl are measured in addition. The reaction vessel is equipped with a series of thermocouples which are located along the vessel axis in 20 mm intervals. During the downward passage of the flame front, the successive response of the thermocouples is recorded. This serves to determine the reaction front velocity.

Figure 2: Schematic diagram of the fixed bed reactor KLEAA



The combustion vessel is described in more detail in Figure 3. The maximum height of the fuel bed is 250 mm and the gas sampling pipe is installed 20 mm above the top of the fixed bed. It has several sampling orifices which are directed towards the fuel bed. The thermocouples in the fuel bed are arranged along two axes close to the vessel center and the distance between the individual thermocouples being 20 mm. The temperature measurement is performed at time intervals of 5 seconds. This arrangement allows determining the temperature distribution in the fixed bed with good spatial and temporal resolution. Moreover, the combustion vessel is mounted on a self-aligning bearing balance for continuous weight measurement. The fuel is batch loaded at the start of a test.

Figure 3: Arrangement of the sampling pipe and the thermocouples in the fuel



Combustion Experiments with Wood Chips as Model Fuel

Commercial wood chips served as reference fuel in the present work and, the combustion process in the fixed bed reactor KLEAA and the derivation of the reaction front velocity as a combustion parameter for quantitative description of combustion are explained in detail now.

Figure 4 shows the overbed concentrations of CO_2 , CO , C_{org} (organic carbon), H_2O , H_2 and O_2 during a combustion experiment with wood chips. In addition, the local air ratio (λ) is plotted on the right axis. The mass flows are calculated from the measured volume concentrations above the fuel bed multiplied by the total volume flow. At the beginning of the experiment, only O_2 is detected above the fuel bed due to the supply of primary air. As a result of thermal radiation from the furnace, the fuel bed surface dries gradually and therefore the H_2O mass flow increases. After about 1.8 min, the fuel ignites, and the mass flows of CO_2 and CO increase rapidly. In addition, C_{org} , H_2 and H_2O are released, while the concentration of O_2 decreases. With the combustion progressing continuously, CO_2 , CO , C_{org} , H_2 , and H_2O are released at roughly constant levels. This period is the quasi-stationary combustion zone, also called main combustion zone. After about 21 min, the O_2 mass flow increases again, while the C_{org} and H_2 mass flows decrease and approach to zero. At this time, practically all of the initial fuel has been consumed and only some residual char is remaining for combustion. Since the primary air flow is constant, the stoichiometry in the reactor increases to a local air ratio > 1 . During this period, the remaining char burns out. After a combustion time of about 45 min, the fuel conversion is completed.

Figure 4: Volume concentration of gas components right above the fuel

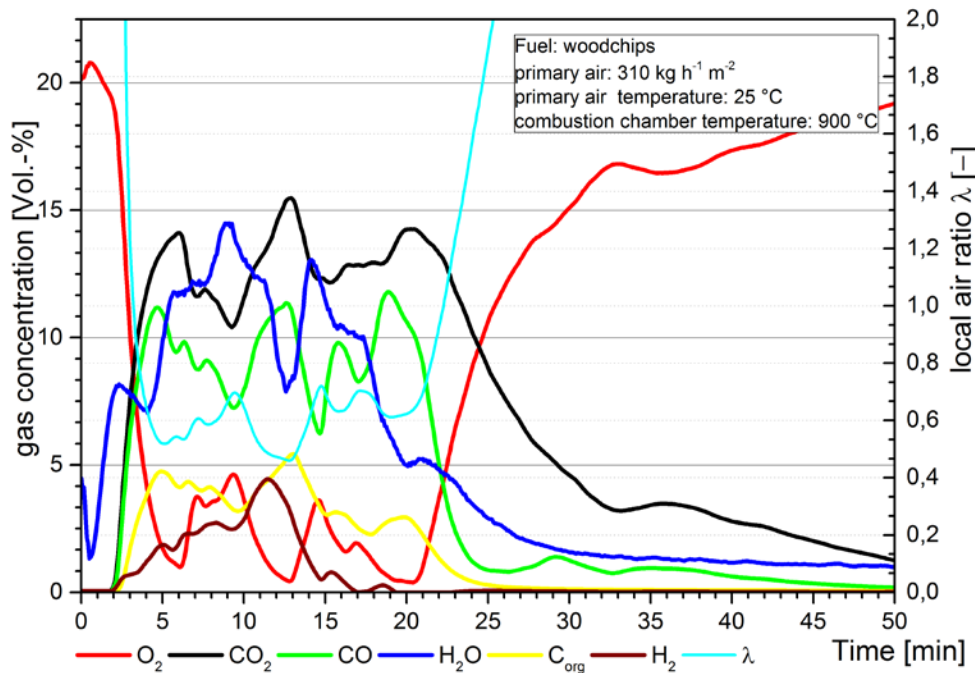


Figure 5 shows the fuel bed temperatures as a function of time. In the ignition phase, the fuel bed surface dries and ignites by radiation heat from the furnace. This is reflected by the rapid increase of the temperature to about 800 °C as measured by thermocouple T2 (blue) which occurs after 1.8 min. The reaction front propagates with an almost constant velocity in a direction opposite to the primary air flow. The temperature profiles of successive thermocouples (Figure 3) are quite

uniform. This indicates a nearly stationary combustion process. At the reaction front, high temperature gradients are generated, and due to the low heat conductivity, the fuel bed remains practically unaffected below the reaction zone. The final temperature rise indicates the char burnout close to the vessel bottom (T13, grey). The determination of the characteristic numbers is summarized in Table 1.

The ignition delay time (t_i) is derived from the inflection point of the temperature curve at the uppermost thermocouple (T2, blue) and is 1.8 min in the present example.

In the main combustion phase, the overbed temperatures are more or less constant. Char burnout is characterized by a further temperature increase. The position of the reaction front is derived from the inflection point of the temporal temperature curves. The positions of the reaction front are represented in Figure 5 for the thermocouples T2 to T13 (magenta, right axis). An almost straight line results. The slope of this line is the reaction front velocity. In the present example of wood chips with water content 15 wt.-%, (these were air dried in the month of the storage from as-cut whole tree chip level of about 50 wt.-%²²), the reaction front velocity amounts to 18.5 mm/min. The ignition rate IR is obtained from the reaction front velocity by multiplication with the measured bulk density of the initial fuel. The third characteristic number, the mass conversion rate MCR, is obtained from the weight loss (Figure 6) divided by the cross section of the combustion vessel and corrected for the amount of ash.

Figure 5: Temperature distribution and the position of the reaction front in the fuel bed

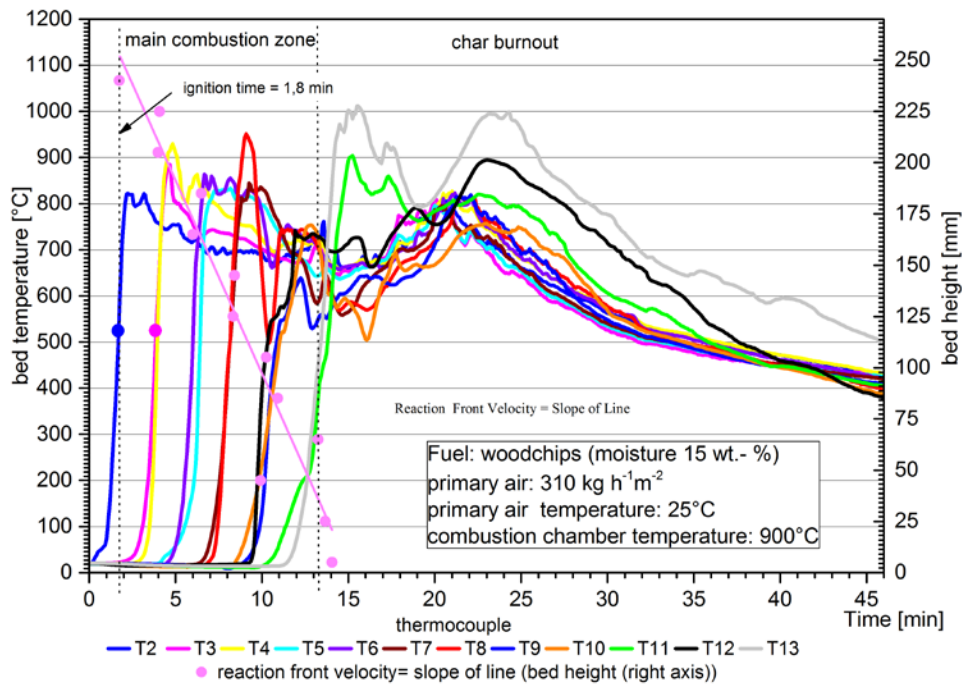


Table 1: Overview of characteristic numbers

Equation 1	reaction front velocity	$u_{RF} = \frac{dx}{dt} \left[\frac{m}{s} \right]$
Equation 2	ignition rate	$IR = u_{RF} * \rho_{bulk} \left[\frac{kg}{s * m^2} \right]$
Equation 3	mass conversion rate	$MCR = \frac{\dot{m}_{fuel}}{A * (1 - \xi_{ash})} \left[\frac{kg}{s * m^2} \right]$
Equation 4	specific heat release rate	$HR = MCR * HHV \left[\frac{MW}{m^2} \right]$

where:

ρ_{bulk} = bulk density of the initial fuel [$kg\ m^{-3}$]

m_{fuel} = fuel mass combusted [kg]

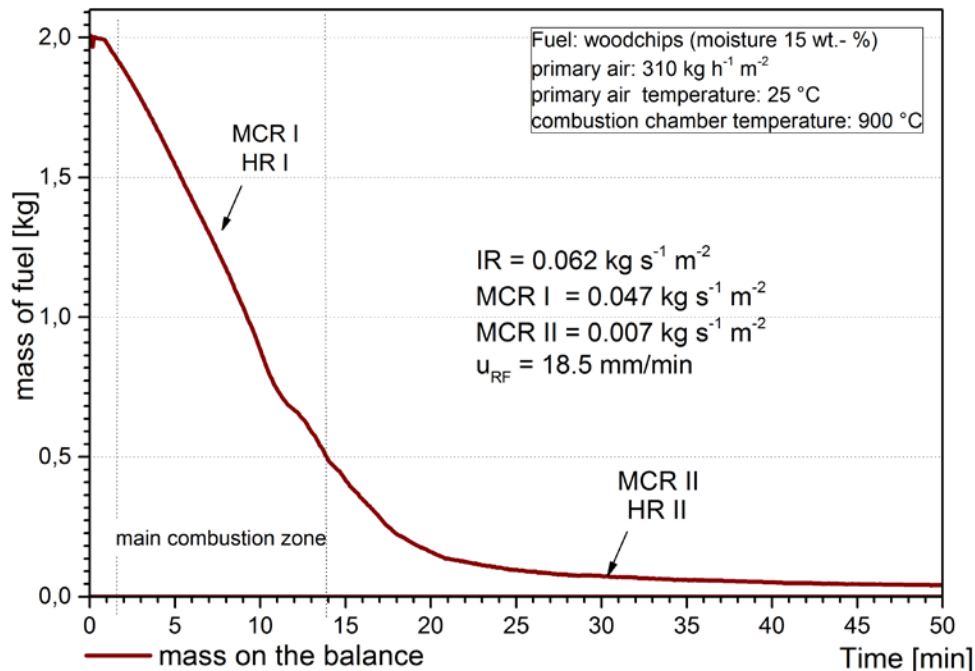
A = cross section of the combustion vessel [m^2]

ξ_{ash} = ash content of the fuel [-]

HHV = higher heating value [MJ/kg]

During the ignition phase, the mass decrease is only due to the evaporation of some water and to some pyrolysis, hence it is almost negligible. In the main combustion phase, the mass decreases linearly. The mass decrease here is defined to be the mass conversion rate I (MCR I). During char burnout, the mass decrease is reduced but remains linear. This is defined to be MCR II. The specific heat release rate HR is calculated from the product of the mass conversion rate and the calorific value. In grate firings, the specific heat release rate should be below $1\ MW/m^2$.

Figure 6: Mass decrease in the fuel bed



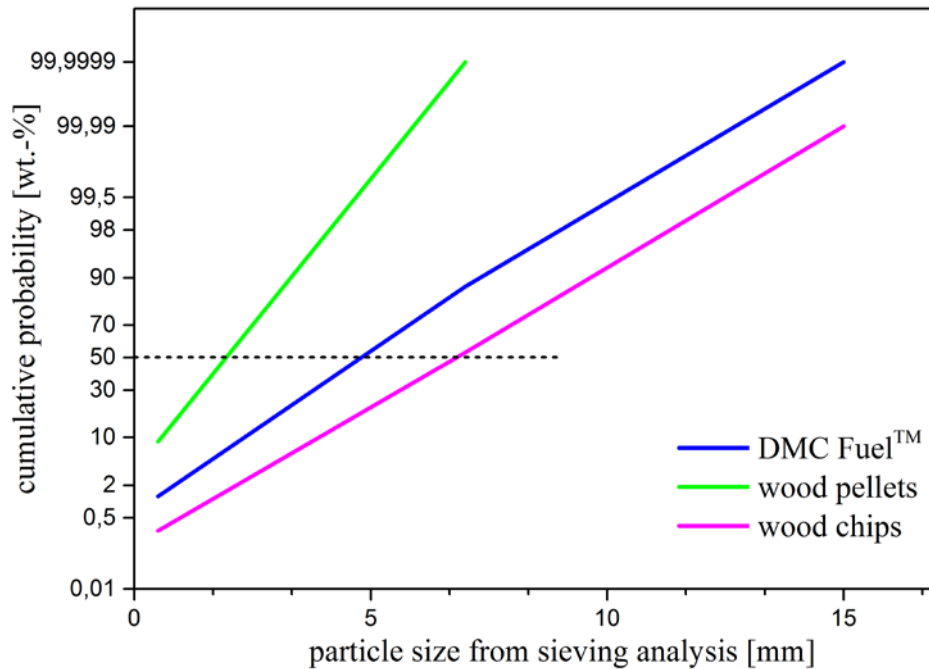
RESULTS AND DISCUSSION

Size Distribution

Figure 7 shows the particle size distributions of the three fuels. Both the mean particle sizes and the width of the size distributions differ significantly. The tested wood pellets were packaged in bagged cargo. They may be broken during the packing, the transport and the unpacking. Also they can break when they were filled into storage. For this reason, their size distribution is not mono-disperse.

As shown in Figure 7, the particle size distributions of the three fuels are nearly Gaussian. The DMC Fuel™ has a mean particle size around 5 mm and a standard deviation σ close to 0.06. This is comparable to the size distribution of the wood chips (mean size ≈ 6 mm, $\sigma \approx 0.09$). The wood pellets, in contrast, have a significantly smaller mean size (≈ 2 mm) and a much smaller standard deviation ($\sigma \approx 0.04$). Since a smaller particle size is associated with a higher specific surface, the wood pellets can be expected to have a higher reactivity. However, due to the higher material and bulk densities, the finally measured mass conversion rate is not increased in comparison to the other fuels (see below).

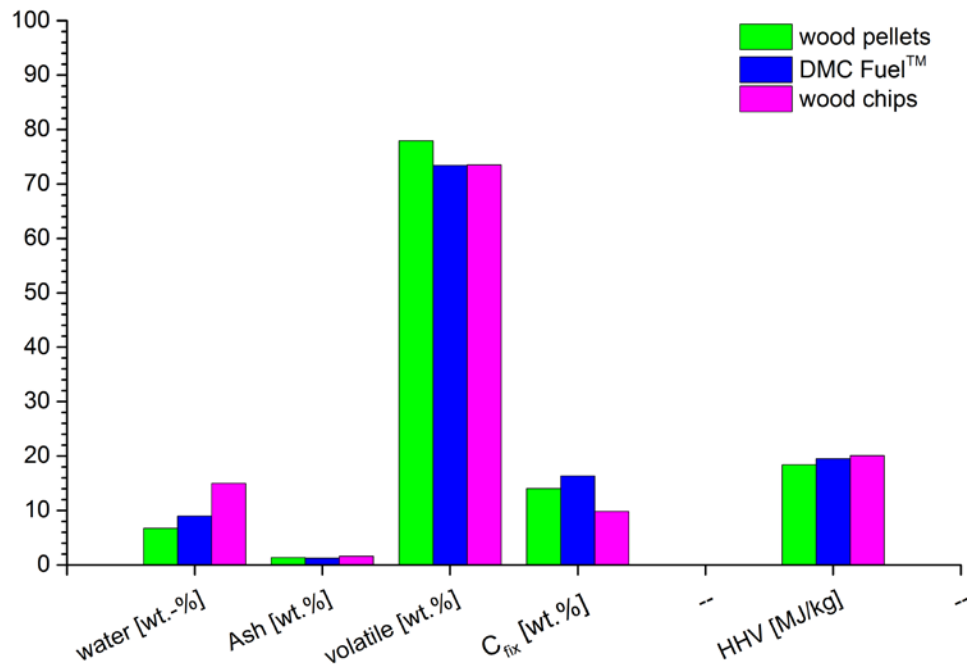
Figure 7: Measured particle size distributions



Analyses

Figure 8 reports the results of elemental and proximate analyses as well as the calorific values. Quite obviously, there are no significant differences between the fuels. In particular, the calorific values are almost identical.

Figure 8: Comparison of the material composition



Characterization of combustion properties of the materials

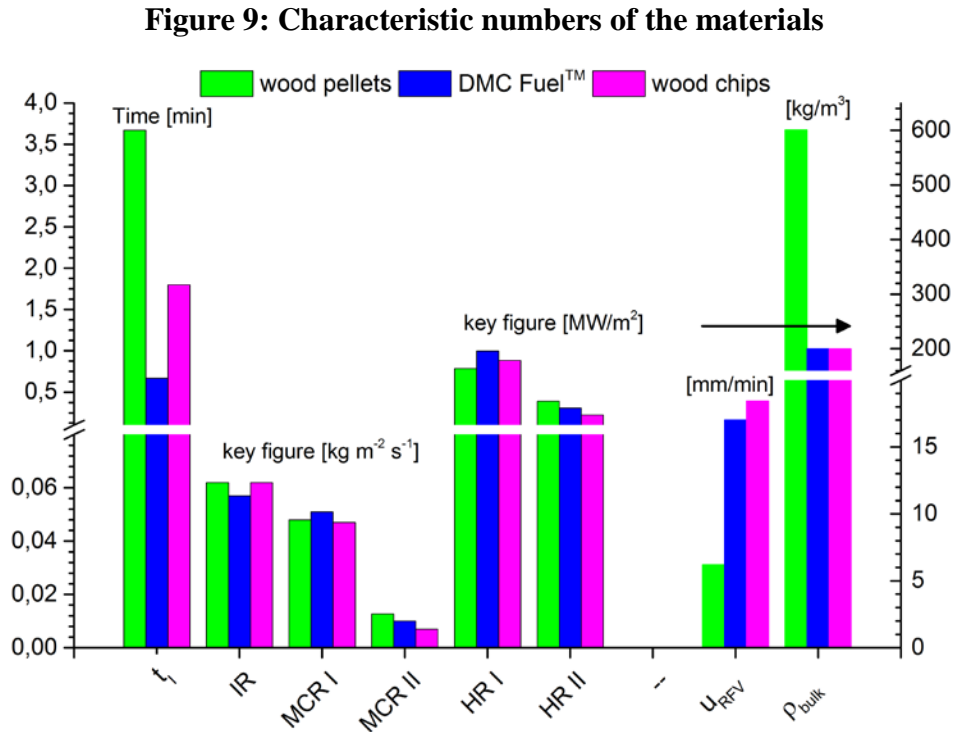
The fixed bed experiments were performed using a primary air flow of $310 \text{ kg h}^{-1} \text{ m}^{-2}$. The temperature of the primary and secondary air were $25 \text{ }^\circ\text{C}$ and the furnace temperature was $900 \text{ }^\circ\text{C}$.

The temperature distributions in the fuel beds were similar for the fuels (Figure 5). During the carbon burnout phase a higher temperature was observed in case of the wood chips ($1000 \text{ }^\circ\text{C}$) than in the case of the other two fuels ($900 \text{ }^\circ\text{C}$). Lower temperatures prevent slagging of particulate residues, especially when they are below the softening temperature of the ash.^{23,24}

In the case of the wood pellets and the DMC Fuel™, the overbed gas concentrations are similar to those measured during the combustion of the wood chips (Figure 4). However, the time required to combust the pellets is around 80 min which is approximately twice as long as in the case of the other fuels. This is because the wood pellets have a higher material and bulk density due to the compression of the material. Therefore, at the same filling height, the total fuel mass in the vessel was three times higher than in case of the non-compressed materials and amounted to 6 kg. The amount of water vapor released from the DMC Fuel™ is about a factor of two higher than in case of the other fuels. This cannot be explained entirely by the difference of initial fuel moisture, see Figure 8. Rather, it indicates a change of the combustion process which is most complete in case of the wood chips and less complete in case of the other fuels. Accordingly, the formation of hydrogen is lowest in case of the wood chips and higher for the other fuels. Moreover, the release of C_{org} also increases in the order wood chips - pellets - DMC Fuel™. This can be explained by the difference in C_{fix} which is lowest for the wood chips and highest for the DMC Fuel™ (Figure 8): C_{fix} effectively competes with the volatiles for oxygen and other gasification media and, the combustion of the volatiles remains incomplete (complete combustion occurs in the post combustion chamber).

The shape of the mass loss rate curves is similar for all fuels and resembles the one shown in Figure 6 with a clear separation of the ignition phase, the stationary combustion phase and the final char burnout phase. The only difference shows up in the quantitative values due to the different initial mass input as mentioned above.

Figure 9 shows the resulting characteristic numbers. Note that the ignition time t_i , the ignition rate IR, the mass conversion rate MCR and the specific heat release rate HR refer to the left axes, while the reaction front velocity u_{RF} and the bulk density ρ_{bulk} refer to the right axes. The corresponding units are indicated directly above the columns.



The wood pellets exhibit the longest ignition delay time ($t_i \sim 3.5$ min) because of their high bulk and material density. The ignition delay time of the DMC Fuel™ is particularly low ($t_i \sim 0.5$ min) because of its low moisture. It may also be due in part to its shape factor, as it has the thinnest minimum dimension and highest surface to volume ratio as compared to the other fuels.

In contrast, the ignition rates IR, the mass conversion rates MCR and the specific heat release rate rates HR are quite similar. The only obvious differences are seen in the reaction front velocity u_{RF} and in the bulk density ρ_{bulk} of wood pellets which differ by a factor of three from the values of the other fuels. As in case of the ignition delay time, this is due to the difference in the material density.

The ignition rates, however, are calculated from the product of u_{RF} and ρ_{bulk} (Equation 2), hence the opposing differences cancel out and the ignition rates are almost equal.

As seen from Figure 9, all characteristic numbers of the fuels are quite similar, hence they are expected to have a very similar combustion behavior in fixed bed and grate firings and probably they can be substituted for each other with the same performance.

SUMMARY

The combustion behavior of three particulate (cm size range) fuels was investigated. Physical, chemical and calorific analyses were found to be insufficient for a conclusive determination and comparison of the combustion behavior. Therefore, the combustion behavior was investigated in a pilot scale fixed bed reactor. Thereby, characteristic numbers were obtained (reaction front velocity, ignition rate and mass conversion rate) which are scale independent and hence applicable to large scale facilities.

The major objective was to investigate the combustion behavior of the novel DMC FuelTM which was compared to those of conventional wood chips and wood pellets. For the wood chips and the DMC FuelTM, the reaction front velocities were found to be 18.5 mm/min and 17 mm/min, respectively, while in the case of wood pellets, a much lower reaction front velocity of only 5.7 mm/min was obtained. Despite some differences in the physical properties and in the chemical properties of the fuels, the other characteristic numbers were found to be very similar. For instance, the ignition rates of the wood chips, the wood pellets and the DMC FuelTM are $0.062 \text{ kg s}^{-1} \text{ m}^{-2}$, $0.062 \text{ kg s}^{-1} \text{ m}^{-2}$ and $0.057 \text{ kg s}^{-1} \text{ m}^{-2}$, respectively. Therefrom, it can be concluded that the combustion performance in continuous grate firings is the same and the fuels can be substituted for each other without difficulty.²⁴

In future experiments, the applicability of the fuels to domestic heating will be investigated by combustion in the newly implemented pellet stove arrangement Apello 13 which currently is being put into operation by KIT.²⁵⁻²⁹ The characteristic numbers obtained during the combustion in the stove will be compared to the fixed bed results. In addition, the fixed bed experiments will be simulated by a numerical model (KLEAA- Code^{16,17}) and the results will be applied to the stove combustion and to continuous grate firings. Finally, the economic efficiency of fuel substitution will be assessed for biomass power plants of various scales on the one hand and for small scale domestic firings on the other hand.

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KEYWORDS

Fixed bed reactor, grate firing, biomass combustion, fuel characterization, characteristic numbers, economic efficiency, wood pellets, DMC Fuel™, fuel efficiency, fuel cost, pellet stoves.