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Wubin Weng1,2, Qiang Gao2,3, Zhihua Wang1, Ronald Whiddon1\*, Yong He1, Zhongshan Li2,3, Marcus Aldén2, Kefa Cen1

*1State Key Laboratory of Clean Energy Utilization, Zhejiang University, 310027, Hangzhou, P.R. China*

*2Division of Combustion Physics, Lund University, P.O. Box 118, SE22100, Lund, Sweden*

*3State Key Laboratory of Engines, Tianjin University, 300072, Tianjin, P.R. China*

*\* Corresponding author: Tel: +86-571-87952111, Fax: +86-571-87951616, E-mail: rjwhiddon@zju.edu.cn*

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Quantitative measurement of atomic potassium in plumes over burning solid fuels using infrared-diode laser spectroscopy

Wubin Weng1,2, Qiang Gao2,3, Zhihua Wang1, Ronald Whiddon1\*, Yong He1, Zhongshan Li2,3, Marcus Aldén2, Kefa Cen1

*1State Key Laboratory of Clean Energy Utilization, Zhejiang University, 310027, Hangzhou, P.R. China*

*2Division of Combustion Physics, Lund University, P.O. Box 118, SE22100, Lund, Sweden*

*3State Key Laboratory of Engines, Tianjin University, 300072, Tianjin, P.R. China*

*\* Corresponding author: Tel: +86-571-87952111, Fax: +86-571-87951616, E-mail: rjwhiddon@zju.edu.cn*

**Abstract:**

Solid fuels, such as coal and biomass, comprise a large portion of the current annual world energy supply, roughly equal to the annual oil consumption. During solid fuel combustion, certain species, though they are fairly benign outside of the combustion system, can cause damage in and around the combustion chamber. Alkali release from coal and biomass is known to cause severe problems in solid fuel fired boilers, such as fouling and corrosion of the heat transfer surfaces. In this work, the amount of atomic potassium in the plume of burning single coal, wood and straw pellets (~170 mg/piece) was measured using tunable diode laser absorption spectroscopy (TDLAS) of the potassium D1 line at 769.9 nm. The sample pellets were burned in an environment with stable temperature and gas composition provided by a laminar flame burner. More atomic potassium existed in the plume of burning biomass pellets comparing with coal pellets, and the two temporal concentration profiles were dissimilar. This was attributed to the difference in the respective combustible components, ash compositions, potassium concentrations and potassium compound state found in the two fuels. A high proportion of fixed carbon in coal induces potassium release mostly during char-burnout period. In contrast, biomass has its strongest release during de-volatilization stage since its potassium presents mostly in a water soluble form. Measurements of atomic potassium concentration during wood pellets gasification were performed in an oxygen deprived hot flue gas environment. The concentration of atomic potassium was found to be halved relative to combustion. The distribution of atomic potassium in the plume at different height above the pellets was also measured and is discussed in brief.

**Keywords:** Potassium; biomass; coal; TDLAS; single particle combustion

1. **Introduction:**

Solid fuels including coal, biomass and solid waste, represent commonly occurring primary energy sources around the world. Coal supplied 30% of global energy production in 2014[1](#_ENREF_1). Biomass is a sustainable and carbon neutral energy resource. Currently, biomass supplies around 10%-15% of world energy demand[2](#_ENREF_2). Combustion is the main approach to solid fuel utilization, which can be found in large scale electricity generation, industrial heating, steam generation, waste destruction, etc.[3](#_ENREF_3) During the combustion of solid fuels, vaporizable alkali species, mainly sodium chloride (NaCl) and potassium chloride (KCl), are released, which lead to problems such as fouling and corrosion of the heat transfer surface in furnaces[4](#_ENREF_4). Due to these phenomena, the study of alkali release during solid fuel combustion continues to be an important area of investigation.

Of the various alkali measurement methods, laser diagnostics number among the few techniques that can offer temporally resolved, *in-situ* alkali measurement. For example, Hsu et al.[5](#_ENREF_5), He et al.[6](#_ENREF_6), Fatehi et al.[7](#_ENREF_7) and Zhang et al.[8](#_ENREF_8) applied laser-induced breakdown spectroscopy (LIBS) in the measurement of sodium and potassium release from burning particles of coal and wood. In these LIBS measurements, total alkali release was measured, irrespective of the chemical bonding states (atoms, chlorides and hydroxides, etc.)[5](#_ENREF_5), [6](#_ENREF_6). From the measured release rate profiles it was possible to model the kinetics of alkali release with a particle model[7](#_ENREF_7). Using excimer laser-induced fragmentation fluorescence (ELIF), alkali species in the flue gases of different solid fuel combustion systems were measured[9-14](#_ENREF_9). Chadwick et al.[15](#_ENREF_15), [16](#_ENREF_16) used this technique to detect NaCl and NaOH released during the pyrolysis and gasification of coal. Using collinear photofragmentation and atomic absorption spectroscopy (CPFAAS), Sorvajarvi et al.[17](#_ENREF_17) detected KCl, KOH and atomic K released from burning wood particles. At elevated temperature, an appreciable fraction of alkali compounds undergoes decomposition, such as a flame front[18](#_ENREF_18); this enables the detection of alkali compounds in fuels through the detection of atomic species. Van Eyk et al. measured the atomic sodium in a burning coal plume using planar laser-induced fluorescence (PLIF)[19](#_ENREF_19). From this measurement, a mechanism for alkali release was proposed[20](#_ENREF_20). While the model accurately predicts sodium release during the char and ash stage, strong laser scattering during the de-volatilization stage prevented measurement; thus, no model validation was possible during that stage. The de-volatilization stage is nonetheless significant in alkali release, especially for biomass which contains a high proportion of volatile alkalis.

TDLAS is a modification of laser absorption technique, which improves signal to noise by scanning rapidly over an absorption transition. It has been used to measure various combustion species[21](#_ENREF_21), such as CH4, CO2, CO, H2O and O2[22-25](#_ENREF_22). Due to the background measurement accrued during the rapid TDLAS scan, this technique offers good performance in sooty measurement environment. Schlosser et al.[26](#_ENREF_26) were able to make absorption measurements by TDLAS of atomic potassium in the flue gas of a high-temperature coal-combustion system. Sepman et al.[27](#_ENREF_27) used it to measure the atomic potassium in the reactor core of a biomass gasifier. Qu et al.[28](#_ENREF_28) applied it to the quantitative measurement of atomic potassium in the burning wood and straw pellets plume. In the present study, TDLAS was used to make quantitative measurements of atomic potassium in the plume of different burning solid fuel pellets to better understand the effects of fuel characteristics and reaction environment on the potassium release process. Three solid fuels were investigated: willow wood, *miscanthus* straw and Zhundong coal. The mass loss of the burning pellets and the local flame temperature were recorded. These experimental data can assist in the development of models for alkali release during the combustion of various solid fuels.

1. **Experimental setup**

**2.1 Laminar premixed burner**

A multi-jet burner, operating in laminar flame conditions, was employed to provide a stable and homogenous thermal and chemical environment, where the fuel pellet was suspended. A 3-D CAD cutaway of the multi-jet burner is shown in Figure 1. The burner is made of stainless steel and features 91 small jet tubes (3 mm O.D. × 1 mm I.D. × 200 mm) ordered in a hexagonal arrangement. These tubes are attached at one end to a gas buffer chamber at the base of the burner assembly. During our experiments the small burner jets supplied a laminar flow of premixed fuel/air. The upper ends of the jet tubes are secured by passing through a perforated metal plate. The geometry of the jet tubes and perforated metal plate is such that each jet tube is surrounded by six 0.5 mm holes in the perforated plate (see Figure 1 (b)). The perforated plate creates the upper boundary of a mid-burner plenum chamber which supplies additional diluent, oxidizer, fuel or a combination thereof. The assembly of small jet burners and perforated plate is contained in a cylindrical steel tube with an inner diameter of 65 mm. The tube is double walled to provide a water cooling. A shielding ring with an inner diameter of 65 mm was placed on the top of the burner, as shown in Figure 1, to ensure even mixing of exhaust gases from the small jets with the co-flow gases at the height of the sample pellet. Also, the shielding ring can isolate mixed hot gas from ambient air to minimize its influence. A flame stabilizer made of a 65 mm diameter steel disc was positioned 40 mm above the shielding ring to further enhance the flow-field stability. The fuel samples were placed 2 mm above the lip of the shielding ring in the center of the burner.

The multi-jet burner was operated at two overall equivalence ratios (**); **= 0.9 for solid fuel combustion and **= 1.1 for gasification. The specific fuel and air flow settings used are given in Table 1. Most measurements were done using condition 1, which supplied excess oxygen to burn the fuel samples. The flow rate of the gases was controlled by mass flow controllers (MFCs, Bronkhorst) and the temperatures of the post flame gases and in the plumes over the burning pellets were measured by a B-type thermocouple (OMEGA). The thermocouple was unshielded to reduce the flow field disturbance in the plumes. Blackbody emission from the thermocouple was visible as it was heated by the hot gas, indicating a significant thermal radiation heat loss and some temperature uncertainty. Hence, the thermocouple was calibrated by another accurate thermometry, i.e. two-line atomic fluorescence (TLAF)[29](#_ENREF_29), and combining the theory of heat transfer[30](#_ENREF_30), [31](#_ENREF_31), the temperature measured by the thermocouple was corrected.

**2.2 Fuel properties**

Three solid fuels were tested in this study. Two are based on renewable biomass: wood (willow), straw (*miscanthus*) and the third is a common brown coal (Zhundong coal, China). The properties of the three fuels are given in Tables 2-4. Table 2 shows the proximate and ultimate analysis of the fuels, which were obtained based on the national standards of China, GB/T 30732 and GB/T 31391, respectively. Table 3 presents the distribution of potassium among various compound classes as determined by chemical fractionation of the respective fuels in successive leaching with water, NH4Acaq and HClaq. After leaching, the residual fuel solids were treated with concentrated HNO3aq, HClaq and HFaq, and heated in a microwave oven. The solution generated in each leaching steps and final concentrated acid treatment were analyzed by induced coupled plasma–atomic emission spectrometry (ICP–AES). Table 4 provides the information on the main elemental composition of the three fuels and their respective ashes through the analysis using energy dispersive spectroscopy (EDS). The ash was produced by burning each fuel sample in a muffle furnace at a temperature of 1088 K based on national standard GB/T 30732, and it may have some difference from the ash formed in the experimental environment with different heating temperature and oxygen concentration (Table 1).

The solid fuel samples were formed into cylindrical pellets with a height and diameter of 4 mm and 8 mm, respectively. Each piece of sample has a weight of around 170 mg. During the measurements, pellets were suspended in the hot burnt gas region above the laminar flame on two ceramic rods, each having a diameter of 1 mm. The heat loss from the rods made the temperature of the gas above the rods drop to ~1530 K. The rods were secured to a balance (A&D) with a precision of 0.01 g, which was used to record the pellet mass loss during the combustion.

**2.2. TDLAS measurement system and principle**

The TDLAS measurement system was aligned to measure the atomic potassium concentration in the region above the suspended fuel pellet, as shown in Figure 2. A tunable single mode diode laser (DL 100, Toptica Photonics) was used, controlled by an analog control package (Toptica Photonics) consisting of a supply/control rack (DC 110), a current control module (DCC 110), a temperature control module (DTC 110) and a scan control module (SC 110). Potassium was detected by scanning over a 25 GHz bandwidth centered at 769.9 nm, the D1 line of atomic potassium. This scanning range was measured by a high-finesse confocal Fabry-Perot etalon (Topoca, FPI 100) and the frequency of the scanning was set to be 110 Hz. A high speed Si photodiode (DTE 210, Thorlab) was used to record the laser energy after a long pass filter (RG 780, Schott) which was used to avoid the saturation of the detector and to suppress the room light and VIS emission from the flame. The signal from the detector was digitized with a data acquisition card (BNC 2110, National Instrument) and averaged 72 times, resulted in a time resolution of 0.65 s.

The absorption measurement is used to calculate the species concentration via Beer-Lambert relation:

, (1)

where is frequency of laser, is laser intensity after passing through an absorbing medium with a path length of and is initial laser intensity. is number density of absorber and is absorption cross-section. The cross-section can be related to Einstein *B* coefficient with the following equation[32](#_ENREF_32),

, (2)

where is Einstein coefficient for absorption, *h* is Planck constant, is central frequency and *c* is light speed. *B*12 can be obtained with:

, (3)

where is Einstein coefficient for spontaneous emission. For D1 line (2S1/2 ⟶ 2P1/2) of atomic potassium, is 3.75×107 s-1 and g1 = g2 = 2.[33](#_ENREF_33)

, (4)

From these equations, the number density of potassium atoms per unit volume can be obtained using the integrated absorbance from the measurement (Equation (4)), assuming that almost all the potassium atoms were at ground state. In Figure 3, the typical raw signal from the detector is shown together with the corresponding absorbance value, . During the calculation, the initial intensity was determined by the fit to the non-absorbing baseline as shown in Figure 3 (a).

1. **Results and discussion**

The pellet swelled in preheating period (early period in de-volatilization stage) and shrank in ash-cooking period. Therefore, the distance between the laser and the surface of the pellets varies throughout the combustion process. In the measurement, the distance at the end of preheating stage, was defined as measurement height, since: a. the size of pellet was fairly constant after an initial preheating which occurred during the de-volatilization stage and through the char burnout stage; b. our investigation emphasizes potassium release during the de-volatilization and char burnout stages where greatest variation in release profile is found.

TDLAS is a line of sight measurement yielding average concentration along the measurement length *l*. The measurement length was estimated by traversing the laser beam horizontally along the axis normal to the laser propagation. The path length is defined by the presence of measurable potassium which is assumed to be axisymmetric. Measurements were made between 300 to 600 seconds after the pellet ignition, when the release of atomic potassium is stable. The horizontal potassium distribution is assumed to be mainly influenced by dilution with ambient hot gas[19](#_ENREF_19). The distribution measured for wood and coal samples were fitted with a Gaussian distribution as shown in Figure 4(a). Normalization of the curves by their respective peak values removes the influence of the potassium concentration from the signal, shown in Figure 4(b); there is no evidence that potassium distribution is sensitive to fuel type in these measurements. According to the normalized curves, the total measurement path length was estimated to be 2 cm, which was close to the size of the glowing flame in de-volatilization stage presented in the photo of Figure 5. Using this method, larger uncertainty in de-volatilization stage may occur, since in this stage the distribution of atomic potassium in the plume could be different from the one assumed in char burnout stage. Further study of the distribution of atomic potassium in the volatile flame is advisable.

Using the path length of 2 cm, the concentration of the atomic potassium in the plume of burning pellets was obtained at a measurement height of 2 mm (Figure 5). Correspondingly, the total amount of potassium atoms at this given height can be calculated out from the measured concentration (Figure 5) and the radial Gaussian distribution of potassium, and it is also presented in Figure 5 respective to the right vertical axis. The error of the atomic potassium concentration measurement can be resultant of the integrated-absorbance calculation, since the scanning range can’t cover the whole absorption peak perfectly. This can make the measurement error up to 20% of the measured value. Moreover, the limit of detection (LOD) of this system was estimated to be 300 ppb, over which absorption saturation happened. However, under saturation condition, the quantitative measurement can still be archived through absorption profiles fitting and simulating, making measurement upper limit to 4 ppm as described by Qu et al. [28](#_ENREF_28).

The three different stages of combustion: de-volatilization, char burnout and ash cooking, can be clearly identified in these traces. The images of wood sample in each stage of combustion are shown as insets in Figure 5. During the de-volatilization stage, the flame glows brightly due to the soot from the burning volatiles. According to the curves, these three fuels feature a de-volatilization stage that lasted among 50 seconds to 100 seconds. The duration of the char reaction stage varied with fuel type; the char burnout for the wood pellet takes 1500 seconds while for coal it takes 3000 seconds.

During the de-volatilization stage, the peak concentration reaches about 75 ppb, 60 ppb and 15 ppb for wood, straw and coal, respectively. During the char burnout stage, wood and coal have peak potassium concentrations of about 25 ppb and 20 ppb, respectively. Their temporal concentration profiles are similar to those collected by Hsu et al.[5](#_ENREF_5) There is practically no discernable potassium release for the straw pellet during the char-burnout.

The measured atomic potassium concentrations are affected by many factors, including fuel composition, potassium concentration, and form of potassium etc. During the de-volatilization stage, atomic potassium is formed primarily through the expulsion of KCl solution which atomizes when heated sufficiently[7](#_ENREF_7), [18](#_ENREF_18), [34](#_ENREF_34) and secondarily the degrading of functional groups that are attached to the char macromolecule, such as carboxyls and alcohols, where potassium substitutes for a hydrogen[18](#_ENREF_18). Atomic potassium formed during the char burnout stage likely comes from the vaporization and dissociation of KOH and KCl [7](#_ENREF_7), [18](#_ENREF_18), [34](#_ENREF_34). As shown in Table 3, the potassium concentration of the biomass fuels is more than 10 times that of coal with more than 90% of potassium in biomass being water soluble versus less than 50% of potassium in coal. This is demonstrated in part by the much greater potassium release during the de-volatilization phase for biomass fuels than for coal (Figure 5).

Proximate analysis (Table 2) shows that wood and straw consist largely of volatile carbon, conversely, coal has a majority of fixed carbon. Because of this, the two biomass fuels lose almost 85% of their mass during the de-volatilization stage compared to 35% for coal (Figure 6 (b)). The biomass samples exhibit a correspondingly shortened char burnout stage in comparison to coal. Fatehi[7](#_ENREF_7) noted that during the de-volatilization stage potassium will react with char macromolecule to form char-K. This potassium will be released during the char burnout stage. For coal, much more potassium is released during the char burnout stage than during the de-volatilization stage, which was also observed in previous research[5](#_ENREF_5), [6](#_ENREF_6).

Comparing the potassium release profile of wood and straw (Figure 6 (a)), it can be seen that the duration of the de-volatilization stage of wood lasts longer than that of straw, which is caused by the overlap between the de-volatilization stage and char reaction stage in the wood which was also observed by other researchers[6](#_ENREF_6), [35](#_ENREF_35). Coincident with the end of the de-volatilization stage, wood char begins to burn which increases the pellet temperature and enhances the potassium release. Comparing the potassium release during the char burnout stage for the two biomass fuel samples, there is almost no potassium release during straw char burnout, mainly because straw biomass has higher fraction of silicon and aluminum (Table 4) which act to secure the alkali materials in the ash fraction[36](#_ENREF_36).

The concentration of atomic potassium in the burning biomass samples, when compared to that of coal, was much lower than what the content of the respective fuel samples would suggest. Some of the reduction is due to the retention of the potassium in the ash residue (Table 4), due to the low amount of char-coordinated potassium and the inert matter components that promote retention of potassium in ash solids (e.g., alumina and silicates). Moreover, differences in the temperature of the plume of the burning pellet influence the atomization of potassium compounds. During the de-volatilization stage, atomic potassium is produced by thermal decomposition of KCl in the high temperature region above the sample pellet; the equilibrium concentration of decomposition reaction dependent on temperature. The temperature traces shown in Figure 6 (c) indicate that the biomass samples experience a temperature drop during the de-volatilization stage of up to 200 degrees. This reduces the concentration of atomic potassium according to the chemical kinetic simulation from Glarborg et al.[37](#_ENREF_37) As a result, the total potassium species released from biomass during the de-volatilization stage should be greater than that from coal, since the atomization of potassium compounds in the region above the biomass pellet is hindered by a lower temperature comparative to the coal de-volatilization stage. Also, for burning biomass pellets, the temperature during the de-volatilization stage is much lower than of the char-burnout stage, as shown in Figure 6 (c). This indicates that the difference between the release of potassium species during de-volatilization stage and that during char-burnout stage should be larger comparing with the difference in potassium atom concentration in Figure 5.

Increasing the equivalence ratio of the laminar burner changes the environment at the height of fuel pellet to be oxygen limited and fuel pellets undergo gasification rather than combustion. The potassium atom concentration in the plume of wood fuel pellets, which was recorded during the gasification process, is also shown in Figure 6 (a). The concentration profile of potassium atom during the de-volatilization stage appears similar to that seen in the preceding combustion experiments, but at a reduced rate, which was also noted by Fatehi et al.[7](#_ENREF_7) Instead of a char-burnout stage there is now a char conversion stage which lacks heat release from combustion of sample materials. This also means that the wood sample does not experience overlapping de-volatilization and char-burnout, thus the duration of the initial potassium release peak is shortened to be approximately equal to that of the straw sample.

The potassium release during the de-volatilization stage is from the vaporization of aqueous potassium solutions at high temperature, as previously mentioned[38](#_ENREF_38). In the study by He et al.[6](#_ENREF_6), alkali release from a fuel pellet suspended in a hot gas mixture of essentially stable temperature but variable O2 concentration (3.9% to 10.6%), showed little influence by O2 concentration. In the present study, the lack of oxygen in the pyrolysis environment meant that the volatile hydrocarbons released during the de-volatilization stage do not ignite as in an oxygen rich environment. This, in turn, lowers the thermal decomposition of the potassium compounds into potassium atoms, resulting in a decreased signal. This is similar to the phenomena noticed when comparing biomass and coal potassium release in the combustion measurements discussed previously. However, the temperature change between the combustion case and gasification case of wood pellets wasn’t observed, as shown in Figure 6 (c). This is because that, in the present study, the temperature in the center of the plume was measured, while the temperature difference mainly produced at the edge of the plume, i.e. the reaction zone of the volatile diffusion flame.

The TDLAS technique can be applied in a sooty environment, supplying quantitative measurement of atomic potassium. These results help to reveal the alkali release process during the combustion of solid fuels. However, the volatile diffusion flame which occurs in the de-volatilization stage complicates the detection and analysis of atomic alkali; the uneven distribution of atomic potassium in the diffusion flame increases the uncertainty in the TDLAS measurement. The concentration is greatly influenced by measurement position, as presented in Figure 7, and the temperature in the plume also shows some variation with the measurement height especially in the de-volatilization stage. In the char burnout stage, the concentration of atomic potassium decreased significantly with the increased measurements height, since the atomic potassium was diluted and oxidized by the surrounding gas[19](#_ENREF_19). In the de-volatilization stage, the concentration initially increased with height up to a point, and then decreased. The vertical position of this trend reversal during the de-volatilization stage varies greatly with the size of the diffusion flame, which in turn, will vary with fuel properties. Because of the interdependence of the flame and atomic potassium distribution, we suggest that further and more detailed study, focusing on de-volatilization stage, is necessary to understand the atomic potassium distribution during this stage of combustion. This will also be useful for other laser techniques such as LIBS and PLIF in which self-absorption by atomic potassium must be considered.

1. **Conclusion**

Tunable diode laser absorption spectroscopy (TDLAS) was used to quantify the concentration of atomic potassium in the plume over a burning solid fuel pellet. Three solid fuels were investigated: coal, wood and straw. The potassium release by biomass is greater than that of coal and mainly occurs during the de-volatilization stage, while coal has its majority release in the char reaction stage. Straw exhibits very little potassium release in the char-reaction stage, unlike what is seen with the other fuel types. The amount of potassium released is expected to be influenced by the potassium compound class, with water soluble potassium compounds equating to high potassium release during the de-volatilization stage. It was found that temperature fluctuations affected the atomic potassium signal due to the influence on the thermal decomposition of potassium compounds such as KOH and KCl, causing a discrepancy between the total potassium released trend and the measured potassium atom concentration profile. This effect was observed during the temperature drop of the de-volatilization stage in biomass fuels which resulted in lower atomic potassium concentrations measured above the burning pellet. To compare the difference in the release behaviors of combustion and gasification, measurements were also made in an oxygen deprived hot gas environment. The maximum concentration of atomic potassium under gasification conditions was half that of the combustion conditions. The reductions were noted in both the de-volatilization and the char-reaction stage. It is believed that the information collected in this study will aid the development of alkali release models that include de-volatilization stage, as the release during this phase represents a significant fraction of total alkali release, and in the case of biomass, the majority of alkali release.

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Table 1. Flame condition for pellets combustion (sl = liter at standard temperature and pressure)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Jets flow rate (sl/min) | | |  | Co-flow (sl/min) | Temperature (K) | Gas composition for pellets combustion (mole fraction %) | | | | |
|  | CH4 | O2 | N2 |  | N2 | CO2 | | H2O | O2 | N2 |
| Flame1  (*ϕ*=0.9) | | 1.32 | 2.94 | 5.17 |  | 4.40 | ~1710 | | 9.5 | 19.1 | 2.2 | 69.2 |
| Flame 2  (*ϕ* =1.1) | 1.54 | 2.73 | 5.17 |  | 4.40 | ~1727 | | -- | -- | -- | -- |

Table 2. Proximate analysis and ultimate analysis of three fuels

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Proximate analysis (%) | | |  | Ultimate analysis (%) | | | | |
|  | Volatile matter | Fixed carbon | Ash |  | C | H | N | S | O(by difference) |
| Coal | 35.75 | 69.12 | 4.64 |  | 64.24 | 3.17 | 0.36 | 0.51 | 19.15 |
| Wood | 80.15 | 18.16 | 1.69 |  | 40.43 | 5.41 | 0.23 | 0.44 | 44.22 |
| Straw | 82.46 | 15.36 | 2.19 |  | 40.75 | 5.37 | 0.11 | 0.42 | 44.25 |

Table 3. Potassium concentration in these fuels

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Potassium concentration (%) |  | Water-leached (%) | NH4Acaq-leached (%) | HClaq-leached (%) | Non-leached (%) |
| Coal | 0.028 |  | 46.5 | 12.9 | 12.9 | 27.7 |
| Wood | 0.369 |  | 94.0 | 4.5 | 0.4 | 1.0 |
| Straw | 0.238 |  | 92.8 | 3.2 | 2.0 | 2.0 |

Table 4. Partition of different element in fuel and ash

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Main element (%) | | | | | | | |
|  |  | C | O | Al | Si | P | S | K | Ca |
| Coal | Fuel | 83.34 | 15.07 | - | - | - | 0.52 | - | 1.07 |
| Ash | **4.34** | **34.28** | **4.94** | **4.86** | - | **12.25** | **0.55** | **26.9** |
| Wood | Fuel | 63 | 36.6 | - | - | - | - | 0.17 | 0.23 |
| Ash | **8.45** | **29.32** | - | **0.83** | **7.67** | **2.48** | **11.5** | **32.41** |
| Straw | Fuel | 59.56 | 38.09 | - | 1.57 | - | - | 0.21 | 0.41 |
| Ash | - | **36.59** | **2.59** | **27.13** | **2.55** | **1.3** | **10.21** | **16.25** |

**Figure Caption:**

Figure 1. Multi-jet burner: (a) 3D cutaway (b) top down view for jet and co-flow arrangement.

Figure 2. Experimental setup of TDLAS for atomic potassium measurement and the position of laser and thermocouple bead in the plume (see inset).

Figure 3. The raw signal from detector (a) and the measured transition profile (b) for scans around the potassium D1 line. Dot grey line in (a): the fit to the non-absorbing baseline.

Figure 4. The horizontal signal distribution above the wood and coal pellets: (a) experimental results (scatter points) and Gaussian fitting (solid lines); (b) normalized Gaussian curves.

Figure 5. The temporal profile of the atomic potassium concentration in the plume of burning wood (a), straw (b) and coal (c) at a measurement height of 2 mm. Photos inset show the burning wood sample during the three combustion stages: de-volatilization stage, char reaction stage and ash cooking stage.

Figure 6. The temporal profile of the atomic potassium concentration (a), the mass loss of burning pellets (b), and the temperature in the measurement zone (c) for each fuel sample in the hot gas environment containing oxygen (*ϕ*=0.9) or without oxygen (*ϕ*=1.1).

Figure 7. The temporal profile of the atomic potassium concentration measured at different position above the wood pellets (a); the average and the peak value of the atomic potassium concentration at different height during the de-volatilization stage (b) and the char-reaction stage (c); the temporal profile of the temperature measured at different measurement height (d). Note: the thickness of wood samples in these measurements was reduced to 1 mm to shorten the burning time.

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Figure 1. Multi-jet burner: (a) 3D cutaway (b) top down view for jet and co-flow arrangement.

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Figure 2. Experimental setup of TDLAS for atomic potassium measurement and the position of laser and thermocouple bead in the plume (see inset).

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Figure 3. The raw signal from detector (a) and the measured transition profile (b) for scans around the potassium D1 line. Dot grey line in (a): the fit to the non-absorbing baseline.

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Figure 4. The horizontal signal distribution above the wood and coal pellets: (a) experimental results (scatter points) and Gaussian fitting (solid lines); (b) normalized Gaussian curves.

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Figure 5. The temporal profile of the atomic potassium concentration in the plume of burning wood (a), straw (b) and coal (c) at a measurement height of 2 mm. Photos inset show the burning wood sample during the three combustion stages: de-volatilization stage, char reaction stage and ash cooking stage.

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Figure 6. The temporal profile of the atomic potassium concentration (a), the mass loss of burning pellets (b), and the temperature in the measurement zone (c) for each fuel sample in the hot gas environment containing oxygen (*ϕ*=0.9) or without oxygen (*ϕ*=1.1).

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Figure 7. The temporal profile of the atomic potassium concentration measured at different position above the wood pellets (a); the average and the peak value of the atomic potassium concentration at different height during the de-volatilization stage (b) and the char-reaction stage (c); the temporal profile of the temperature measured at different measurement height (d). Note: the thickness of wood samples in these measurements was reduced to 1 mm to shorten the burning time.