Syngas production from residual biomass of forestry and cereal plantations using hybrid filtration combustion

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Abstract

This work shows and discusses the experimental results obtained from hybrid filtration combustion using biomass pellets originating from cereal plantations and forestry industry, which are some of the most common residual biomass sources in Chile. The biomass is made from oat cane, wheat cane, shining gum (Eucalyptus nitens) and insignis pine (Pinus radiata). The experiments were carried out using a porous media reactor filled with biomass pellets and alumina spheres in equal volumetric quantity. The gasifying agents used were a natural gas-air mixture (equivalence ratio Φ=1.1) and an air-steam flow, in which the steam content varied from 20 to 40% of the initial air flow, changing filtration velocity from 26.1 to 31.3 and 36.5 cm/s, respectively. Using natural gas, temperature increased only using insignis pine while the usage of cereal plantation residuals enhanced syngas production. Maximum syngas production was achieved using wheat cane, obtaining 50% more H_2 and 97% more CO than the base line. Using steam, temperature of combustion was slightly influenced by a steam presence increase. Also, H_2 production was only enhanced using wheat cane and insignis pine, while CO production was lower than the base line in every case. Maximum H_2 and CO production were obtained by the base line of shining gum, showing that the presence of steam disfavors syngas production in most cases.

Keywords: Hydrogen, Syngas production, biomass, filtration combustion, gasification.

1. Introduction

Nowadays, the importance of developing clean fuels has been increasing due to strict environmental standards on emissions that affect the use of common hydrocarbon fuels. In this context, hydrogen has been gaining attention by being considered as the energy carrier of the future [1]; its high energy content per mass [2], clean combustion (with air it only generates water steam and nitrogen oxides) and since it is not available in nature; new, innovative and economic techniques to produce it are strongly necessary. Moreover, hydrogen is a high value chemical, widely used in chemical and petrochemical industries in several processes such as the Fischer-Tropsch, ammonia production or Hydrocraking. Attractive applications of hydrogen's use for high efficiency electricity production via fuel cells are being studied, projecting it even as an alternative to transportation fuels, internal combustion engines and electric/hybrid vehicles in the automobile industry [3-5]. However, some difficulties still affect the use of hydrogen as a massive consumption fuel; among the most important are production, storage, distribution, safety and public perception [6].

Hydrogen can be produced from several processes and sources. Reforming of hydrocarbons, specially steam reforming of methane, is the leading process for hydrogen industrial production [7]. Partial oxidation, catalytic partial oxidation of gaseous and liquid hydrocarbons, electrolysis, and photolysis among other technologies are available for hydrogen production, which are less economically feasible. Nevertheless, these processes produce carbon dioxide as a by-product [8], require high energy supply, high pressure or the presence of expensive catalysts.

On the other hand, biomass provides 10% of the primary energy resources in the world [9]. Gasification of biomass is able to produce hydrogen and its use is considered environmentally friendly due to the use of fuels coming from natural carbon dioxide consumers, assented as CO_2 neutral and having very low sulfur content [10].

Hybrid filtration combustion introduces a process that combines the properties of filtration combustion in inert porous media, which consists on exothermal waves of reactions that propagate in a porous medium -that has been well described and studied [11-17]- and solid fuels gasification, allowing the usage of renewable energy solid fuels, by replacing a fraction of the inert solid's volume for a solid fuel. Experimental hybrid filtration combustion has been studied for syngas production using carbon [18], coal [19], wood pellets [20] and polyethylene [21] among other solid fuels and a mathematical model based on mass and energy equilibrium equations has been proposed [22-23]. Salgansky et al. [19] studied and modeled [22] the filtration combustion of a steam-air flow in a porous media composed on carbon and inert solid material; temperature in the combustion wave and product composition are obtained varying the carbon fraction (from 10 to 100%) and steam (varying water/oxygen from 1 to 4.5) present in the oxidant. The maximum combustion wave temperature showed a slight dependence on the porous bed composition and steam presence. An increase in steam presence in the oxidant lead to a rise in hydrogen concentration in the gaseous products and caused a decrease in carbon monoxide concentration. Coal experiments were done using a rich natural gas-air mixture and varying the porous bed composition from 0 to 75% of coal pellets; it was observed that hydrogen yields and flame temperatures increased by augmenting filtration velocity and that flame temperatures decreased with an increase of the coal fraction of the porous bed; maximum hydrogen conversion was achieved with 75% of coal content in the porous bed [19]. For wood pellets (50% alumina spheres, 50% wood pellets in volume), rich and ultra-rich combustion of butane experiments, hydrogen and carbon monoxide are the dominant products and compared with the inert porous media partial oxidation of butane, a higher presence of syngas in the products is reported [20], showing that wood presence boosts syngas production. Recent research has shown that syngas can be produced using wood pellets in a lean mixture of natural gas-air filtrational combustion [24], varying the equivalence ratio from 0.3 to 1, obtaining the maximum hydrogen conversion (~ 99%, related to the filtered mixture) at $\Phi=0.3$.

A significant part of Chilean industry is based on cereal plantations and forestry activities. These industries produce large amounts of residuals which are a major source of biomass. In order to evaluate the employment of these sources for hydrogen production using hybrid filtration combustion, a selection of the most common biomass sources in Chile is achieved considering that forestry plantations are mostly focused on insignis pine (Pinus radiata) and shining gum (Eucalyptus nitens) [25] and cereal plantations are focused on oat and wheat cane. The availability of these biomass sources makes their use very attractive for energy and syngas production, especially considering that the biomass is usually burned as waste without further purpose.

This work assesses the use of the most common and available biomass sources from industrial residuals in Chile, for the production of syngas using hybrid combustion filtration with 50% of the porous media volume reactor occupied by biomass, and the influence of the gasifying agent is evaluated by using a mixture of natural gas-air ($\Phi=1.1$) and a steam-air flow as an oxidant, varying filtration velocity. This work can be divided into two parts: Part 1: usage of natural gas-air premixed filtration combustion and Part 2: using a saturated steam-air mixture and varying filtration velocity. Temperature and product characterization are obtained experimentally to describe and evaluate hydrogen and syngas production.

2. Preparation of biomass and characterization

As biomass is presents in various forms and is obtained from several sources, conditioning and preparation is necessary prior to its use. Biomasses with elevated moisture content were sun dried. Once biomass reaches between 5 to 15% of moisture, a hummer mill reduces particle size and separates particles using sifters. The milling process also contributes to the biomass drying process due to the heat produced by friction between biomass, sifters and hummers. Pelletizing is achieved using a GC-ZLSP120B pelletizing machine that cuts, mills and compresses the biomass. From the different biomass sources, HHV, moisture and ash content were obtained and LHV was calculated. An elemental analysis (m%) was carried using a Thermo Finnigan EA 1112 Series Flash elemental analyzer; values are shown in Table 1.

Table 1. Heating values, moisture and ash content and elemental analysis for the biomasses.

	Shining gum	Insignis pine	Oat cane	Wheat cane	Method
HHV [kCal/kg]	4630	4305	4021	3997	ASTM D-240
LHV [kCal/kg]	4308	4010	3735	3697	Calculated
Moisture [%]	0.59	6.38	7.81	6.53	ASTM D-95-70
Ash content [%]	0.80	0.38	3.28	3.88	ASTM D-3174
C [%]	48.33	51.27	46.76	46.61	Thermo Finnigan EA 1112 Series Flash elemental analyzer
H [%]	5.89	6.19	5.62	5.72	
O [%]	45.13	42.13	39.63	40.97	
N [%]	0.15	0.13	1.23	1.21	
Others [%]	0.50	0.28	6.76	5.49	

3. Experimental setup

The experimental setup used for the characterization of syngas production using different sources of biomass is shown in Figure 1. All the experiments were carried out in the same reactor For the steam-air flow (part 2), some modifications to the setup shown in Figure 1 were necessary as shown in Figure 2.

The reactor consists on a quartz tube (362 × 42 × 46 mm, length × ID × OD). This quartz tube was filled with a 1:1 volume mixture of randomly deposited alumina spheres (Al_2O_3, 5.6 mm D) and biomass pellets (5.6 × 5.2 mm, length × D), forming a porous medium with ~40% porosity. Internal and external surfaces of the reactor were covered with thermal insulation for minimal heat loss; the internal surface was covered with ceramic fiber (Fiberfrax, 2 mm thick) and the external surface with fiberglass (20 mm thick). For the steam flow a copper pipe (83 × 6 mm, length × D) was included in the inert zone 2 of the reactor.

Reactants flows were measured using Aalborg Mass Flow Controllers (GFC 17) for air and natural gas (92% CH_4) flow. Natural gas and air flows were premixed in a mixing chamber. Steam was generated from boiling water using electric resistances and the saturated steam flow was controlled measuring the steam production and varying the power supplied by electric resistances. Control of steam production was achieved by measuring the volume of condensed steam that flowed into a container after one minute.

Combustion temperature data was obtained using six S-type thermocouples that were set inside a ceramic tube disposed in the center of the reactor, with bores that allow thermal contact with the medium, providing temperatures close to the solid phase; thermocouples were labeled T1 to T6. Data was collected and recorded using an OMB DAQ 54 acquisition module and processed by the Personal DaqViewPlus Software (OMEGA Engineering Inc. USA). Bores of the ceramic tube were equally spaced with 30 mm distance from each one starting 70 mm from the top of the reactor. A Temperature data error of 50 K is estimated, mainly radial for practical purposes.

Samples of combustion products were taken at the top of the reactor using a tube inserted 30 mm in the porous medium (inert zone 1), extracting gas products into a carrying bag to analyze the presence of hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and carbon dioxide (CO_2), using a Perkin Elmer Gas Chromatograph. The experimental sampling error was estimated at 10%.

4. Experimental procedure

Part 1 consists on experiments using filtration combustion of a natural gas-air mixture (Φ=1.1, filtration velocity u=26.1 cm/s) over a porous medium containing biomass pellets and alumina spheres in equal volume, varying only the biomass source and maintaining volumetric proportions. For these experiments, a base line has been established by performing natural gas-air filtration combustion through a porous medium composed only of alumina spheres (creating a chemically inert medium) in the same reactor shown in Figure 1 using Φ=1.1 and u=26.1 cm/s.

Part 2 carries the experiments changing natural gas-air flow for a steam-air flow, in this case, air flow is fixed and steam flow is varied within 20 and 40% of the air flow, this means that filtration velocity varies by increasing steam presence between 31.3 and 36.5 cm/s. This mixture is filtered through the porous medium. Also the base line was established by the filtration of air (0% steam) in the hybrid medium with u=26.1 cm/s.

As temperature data could instantly be observed while the experiments were being carried, for Part 1 product sampling was performed when T3 showed a maximum temperature and for Part 2 sampling was performed when T2 showed a maximum, mainly due to a position change of the hybrid medium between Parts 1 and 2 as shown in figures 1 and 2. A maximum temperature in a thermocouple shows that the combustion wave is passing through the same position or close to the location of the thermocouple. These combustion waves move across the reactor depending on various factors, but the propagation dynamics can be mostly controlled with equivalence ratio and heat transfer mechanisms, thus, in Part 1 the combustion wave moves upstream and is started using a lighter at the top of the reactor.

For Part 2, as the gasifying agent is steam and air only, a combustion wave cannot be started as in Part 1. Therefore, inert zone 2 is pre-heated using a natural gas-air flow (Φ=0.8, u=26.1 cm/s) until a maximum temperature is reached in T6. Then natural gas flow is closed and steam-air flow is filtered in the reactor. In this case, the combustion wave moves downstream.

5. Results and discussion

Experimental results are shown by means of combustion temperature, propagation rate of self-sustained waves and product gas chromatography characterization of H_2, CO, CH_4 and CO_2.

Part 1: Combustion wave temperature

Combustion wave temperature was obtained and is shown in Figure 3; these temperatures correspond to the maximum obtained in the temperature profile recorded in the experiments. The temperature obtained as a base line is 819°C. From the results, only the temperature obtained with insignis pine was above the base line, while other results showed lower combustion wave temperatures. As filtration velocity and the equivalence ratio are not changed, these temperature differences may be caused by the chemical heterogeneous reaction mechanisms. The highest combustion wave temperature was obtained using insignis pine (968°C).

Part 1: Combustion wave propagation rate

Propagation rate of the combustion wave can be obtained by following tendencies on the peaks or a given value as reference from temperature data as a function of time, relating it to the fixed position of the thermocouples in the reactor. A peak in temperature indicated by the data acquired suggests that the combustion wave is passing through the same position as a determined thermocouple is located. However, temperature data did not show any tendency on temperature behavior that could relate position and time of the measurement, thus a combustion wave propagation rate for this part was not possible to obtain. Nevertheless, data acquired for the base line allowed to determine a propagation rate of 0.0036 cm/s, very close to the numerical prediction and empirical results of Toledo et al. [14].

Part 1: Combustion products

Characterization of products from the reaction is very important to evaluate the process capacity to produce syngas and the suitability of these biomasses for this purpose. H_2, CO, CO_2 and CH_4 volumetric concentrations in the products were obtained and are shown in Figure 4. CO_2 is an indicator of how complete the combustion was; a high presence of CO_2 is expected when oxygen is provided in enough quantity to fully oxidize gas and solid fuels, which is not the case. On the other hand, H_2 and CO indicate the presence of intermediate products of complete oxidation and therefore that an incomplete combustion has been performed.

For hydrogen production, forestry residuals showed lower levels than the base line, while cases that used residuals from cereal plantations presented higher concentrations than the base line. Interesting results were obtained using wheat cane; maximum hydrogen production was achieved, producing 50% more hydrogen than the base line, followed by oat cane that generated 31% more hydrogen than the base line. For CO, the results are similar to the hydrogen production; CO production using forestry residuals are lower than the base line and using cereal plantations residuals, results were higher than the base line. High CO presence was obtained using wheat and oat cane, generating 97% and 58% more CO than the base line, respectively.

CH_4 presence is related to the unreacted fuel that was used as a gasifying agent or to a product of the gasification process (contained in the producer gas), so a significant presence of CH_4 indicates that the oxygen carried in the filtered mixture was used for the oxidation and gasification of the solid fuel instead of the combustion of CH_4, as the base line indicates its absence in the products of inert porous media combustion (base line=0% CH_4). Gasification of the solid fuel is intuited due to an upstream wave movement through the reactor that would mean that the reactions occurring in the reaction zone are in presence of the reaction’s thermal conditions and the oxygen that has not been consumed yet. Insignis pine, shining gum and oat cane showed a significant presence of CH_4 in the products, where insignis pine had the highest concentration, which could be related to the chemistry of the reactions, prioritizing biomass instead of natural gas combustion, heading to an important increase of the combustion temperature as shown in Fig. 3. The results showed that CO_2 presence was lower than the base line in every case, as expected, because the filtered mixture is rich and the solid fuel also consumes oxygen, in other words, the hybrid case has more oxygen consumers and therefore less reactants are able to achieve complete combustion.

Taking in consideration that using shining gum and insignis pine results showed the lowest concentrations of H_2 and CO, and that it could also be noticed that with these biomasses the highest levels of CO_2 and CH_4 are obtained. Empirical data suggest that the reaction mechanism tends to use the available oxygen (limiting reactant) in the oxidation of the solid fuel. On the other hand, for oat and wheat cane the reaction mechanisms tends to use oxygen to partially oxidize methane from the reactants to produce H_2 and CO while it is reflected in low CO_2 and CH_4 presence, more intensively observed in the results of wheat cane, where the reaction fully consumed CH_4.

Part 2: Combustion wave temperature

Combustion wave temperature data obtained is shown in Figure 5 for hybrid filtration combustion of biomass and steam-air mixture. Reports of Araya et al. [26] showed that for inert filtration combustion of methane and steam, using $\Phi=1.4$, an increase on steam presence on the reactants that entails an increase in filtration velocity lead to a decrease in the temperature; the same behavior using carbon is shown by Salgansky et al. [18] that increased steam presence in the reactants to report a decrease in the combustion temperature, so similar results are expected owing to the endothermic reactions that involve steam decomposition.

Shining gum results showed the highest combustion wave temperatures. This is attributed to the heating value and the moisture content in the solid fuel; shining gum has by far the highest HHV and the lowest moisture content of the biomasses considered in this study, meaning that the reactions that use other biomasses have less energy available to release from the combustion and a higher moisture level involves the use of energy released from the reaction to dry the solid fuel instead of showing higher temperatures of combustion.

Otherwise, an increase in the presence of steam in the gasifying agent and filtration velocity shows slight influence in temperatures for the experiments. Insignis pine, oat and wheat cane evidence a small decrease in temperatures compared to the base line as expected, although, shining gum was the only case in which temperatures are higher than the base line. Also, results for shining gum, oat and wheat cane show that temperature increases by rising steam presence and filtration velocity, which could be related to a more efficient heat release from the solid fuel using more steam and a lower residence time of the gasifying agent. On the other hand, insignis pine combustion decreased temperature by rising steam and filtration velocity, as expected.

Part 2: Combustion wave propagation rate

Propagation rate of the combustion wave was obtained as explained in part 1 by following tendencies of temperature taking as a reference the value 800°C and is shown in Figure 6. Propagation rate is related to the thermal conditions shaped by heat transfer mechanisms, therefore, reaction zone movement obeys to a tendency of the reaction to occur in a place with better condition for the reaction development: it is expected that by incrementing the gasifying agent presence and filtration velocity, reaction mechanisms are accelerated and propagation rate is increased.

Regarding to the base line, results exhibit an incremented propagation rate by adding steam using shining gum, insignis pine and wheat cane, while using oat cane with 20% of steam, the propagation rate was lower than the base line and with 40% of steam, a rate higher than the base line was achieved. The maximum propagation rate obtained was 0.229 mm/s, performed by oat cane with 40% of steam, being 19% faster than the base line. Shining gum was the most influenced case by steam adding, being 45% faster than the base line using 40% of steam.

For shining gum, insignis pine and oat cane results showed that the propagation rate increased by incrementing steam presence from 20 to 40% and filtration velocity, as expected. However, propagation rate for wheat cane decreased by augmenting steam presence.

Part 2: Combustion products

The combustion product characterization is shown in Figure 7. Since the combustion wave moves downstream through the reactor and oxygen is provided as a limiting reactant, pyrolysis is intuited to occur as the reaction wave moves, because reaction in the solid fuel happens at the high temperature condition of combustion and the presence of combustion products, therefore, oxygen absent ambience. It is expected that by increasing steam presence, H_2 concentrations increase in the products because reactions have more hydrogen available in the reactants, also has to be considered that in inert porous media combustion, an increase in filtration velocity lead to an increment in Temperature, H_2 and CO yields [14], mainly because of lower residence times of the filtered reactants. This behavior is observed as expected with steam addition and the increase of filtration velocity, as in every case H_2 presence in the products increased. However, comparing results with the base line, things are different; shining gum and oat cane evince lower H_2 concentrations in the products, compared to the base line; insignis pine and wheat cane showed lower H_2 presence than the base line when using 20% steam and higher H_2 presence when using 40% steam in the reactants. Also a significant difference has been noticed in the results with steam addition and the base line using shining gum that could be attributed to the low moisture content in the biomass. CO concentrations showed lower levels than the base line, notwithstanding oat cane case, that evince slight increase in CO production with steam presence in the reactants. Incrementing steam presence in the reactants increased CO generation except using shining gum. As CH_4 is not a reactant per se, it is interesting its significant presence in the products. CH_4 is attributed and is considered a proof of pyrolysis; it comes as a component of the producer gas from the reaction and is not oxidized regarding to the oxygen absence, but it could be affected by steam reforming reactions under the thermal conditions of the reactor. CH_4 presence increases by adding steam to the filtered mixture except using shining gum that shows a decreasing behavior. For insignis pine and wheat cane, CH_4 has similar results for H_2; using 20% of steam, CH_4 presence is lower than the base line and using 40%, higher concentrations than the base line are obtained. Also, insignis pine, wheat and oat cane showed an increase in CH_4 presence by adding steam to the gasifying agent. Lower CH_4 concentrations than the base line and a decreasing behavior by adding steam and increasing filtration velocity are observed for shining gum. On the other hand, CH_4 presence higher than the base line is noticed with oat cane by adding steam.

In inert filtration combustion, is reported that CO_2 concentration for Φ=1.4 decreased as steam presence and filtration velocity augmented [26], which is also observed in the results for hybrid filtration combustion, in spite of insignis pine results. As steam is increased from the base line to 40%, CO_2 presence decreases. Insignis pine was an exception, showing significantly higher CO_2 concentrations as steam presence increased.

From the results, steam presence only improved H_2 concentrations using insignis pine and wheat cane, producing 35% and 13% more H_2 than the base line, despite the highest H_2 production by the base line of shining gum. Steam addition does not contribute to improve CO production, in fact the highest concentrations were obtained by the base lines, except using oat cane that showed very low CO production but obtaining 90% more CO than the base line.

6. Conclusions

Hydrogen and syngas production has been analyzed in this work for several biomass pellets and alumina spheres in hybrid filtration combustion of natural gas-air and water steam-air mixtures. Insignis pine, shining gum, wheat and oat cane were considered and showed that a self-sustained combustion wave can be obtained under these conditions.

Regarding the experiments performed with natural gas, an upstream propagation of the combustion wave was observed; temperature was higher than the base line only using insignis pine and the usage of cereal plantation residuals enhanced significantly syngas production. On the other hand, forestry residuals presence in the hybrid medium did not contribute to syngas production, obtaining even lower concentrations than the inert filtration combustion case. Maximum H_2 and CO production was obtained using wheat cane, achieving 50% and 97% more H_2 and CO than the base line, respectively.

Downstream propagation of the wave was observed with air and steam. Propagation rate increased by incrementing filtration velocity as expected, except using wheat cane. Temperature of combustion was slightly influenced by steam addition and the increase of filtration velocity. Also, steam addition contributed to enhance H_2 production only with wheat cane and insignis pine, while CO production was lower than the base line in every case as steam presence was increased. Maximum H_2 and CO production were obtained by the base line of shining gum (using air only), showing that the presence of steam disfavor syngas production in most cases.

Results of this study suggest than the usage of cereal plantation residuals in the hybrid filtration combustion of natural gas has the potential to produce H_2 and CO enhancing the process, but further studies that aim for the conditions that maximize syngas production are required, i.e. varying equivalence ratio and biomass percentage in the porous medium.

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Figure Captions

Fig. 1. Experimental setup schematic (dimensions in mm).

Fig. 2. Experimental setup schematic for part 2 with steam inlet modifications (dimensions in mm).

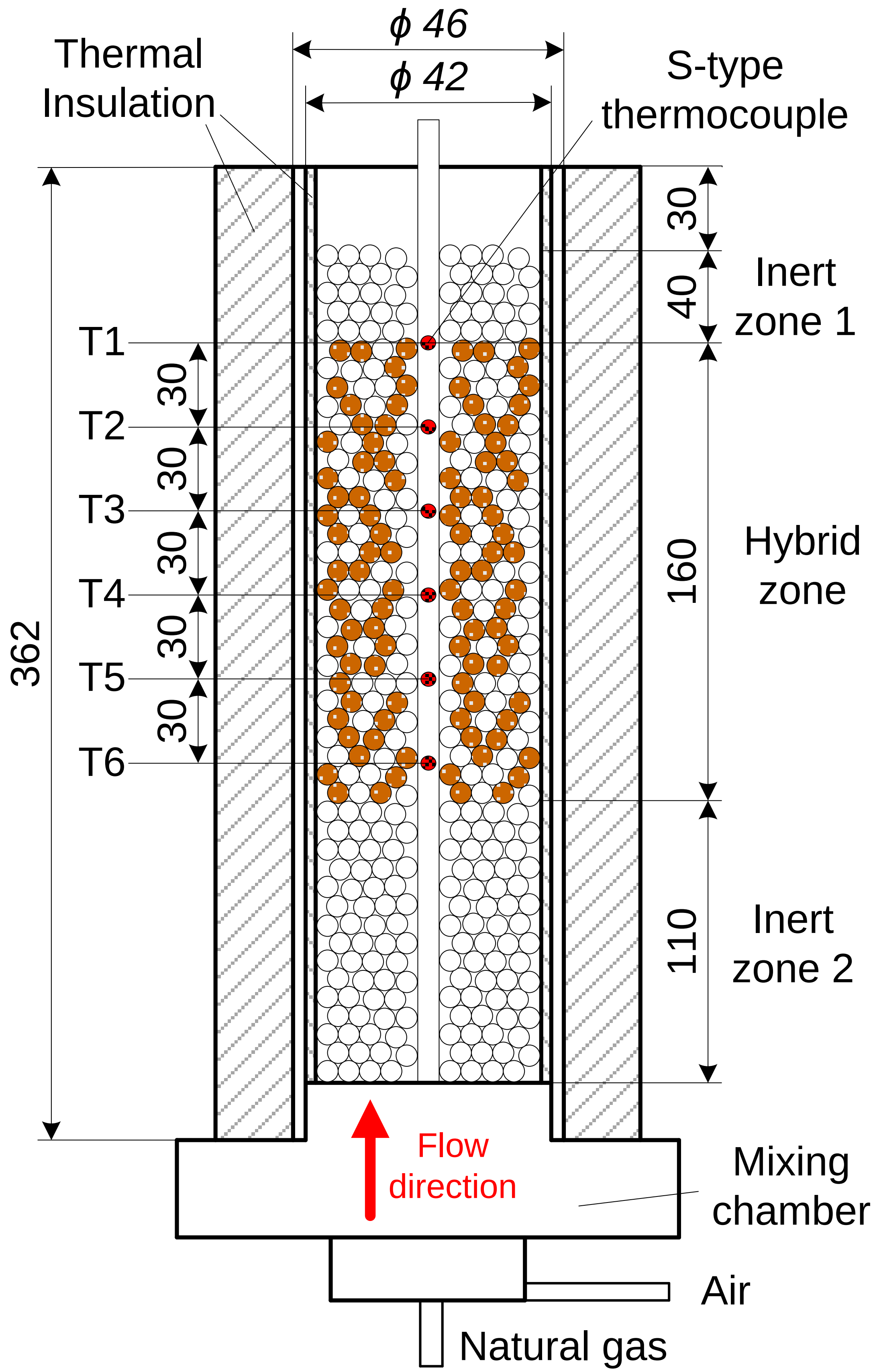
Fig. 3. Combustion wave temperature for hybrid filtration combustion of natural gas-air mixture and the base line (inert medium).

Fig. 4. Experimentally measured volumetric composition of products from hybrid filtration combustion of natural gas-air mixture and base lines for the biomass; A) Hydrogen, B) Carbon monoxide, C) Methane, D) Carbon dioxide.

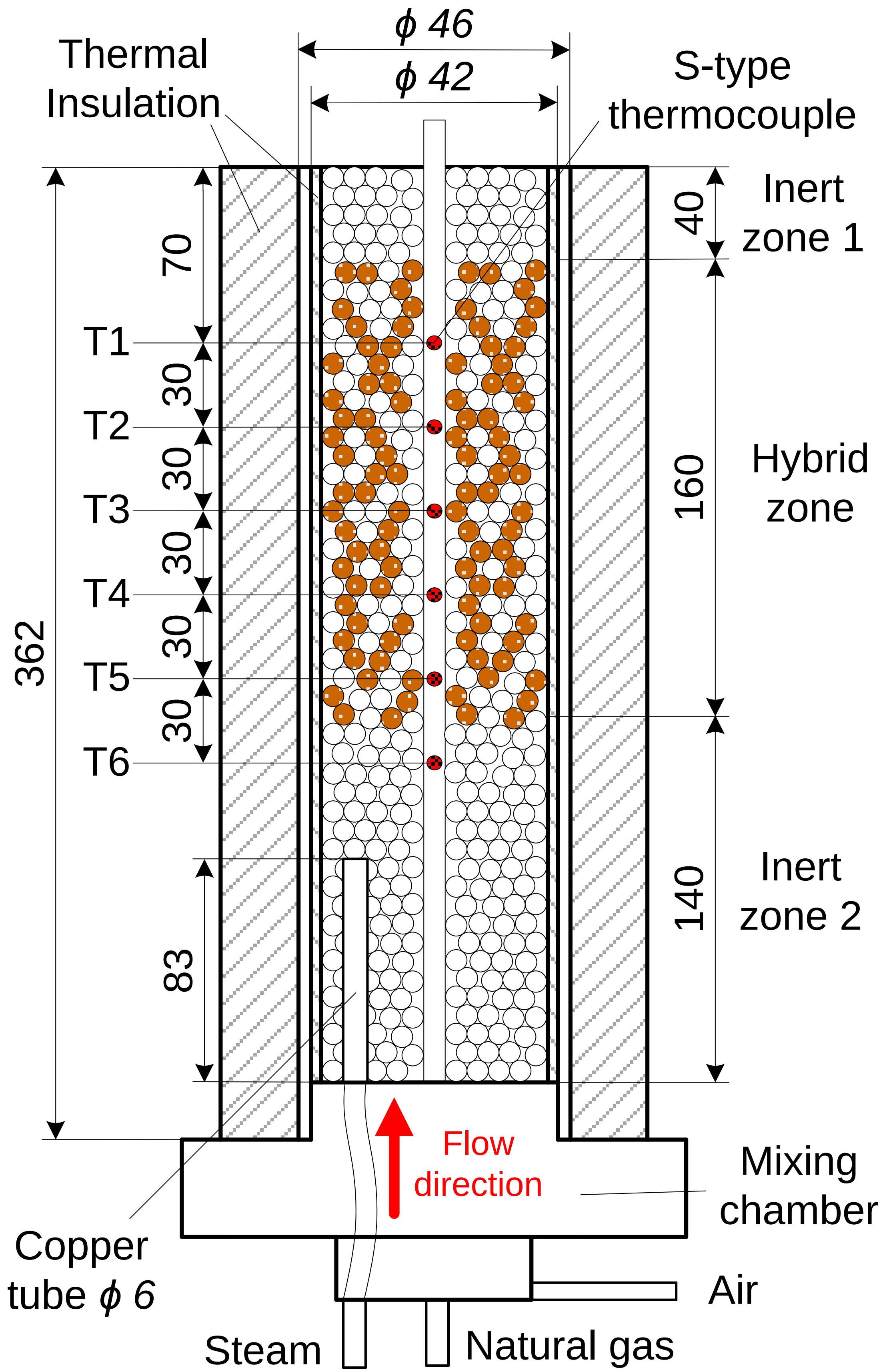
Fig. 5. Combustion wave temperature for hybrid filtration combustion of steam-air mixture and the base line (air only).

Fig. 6. Propagation rate of the combustion wave through the reactor.

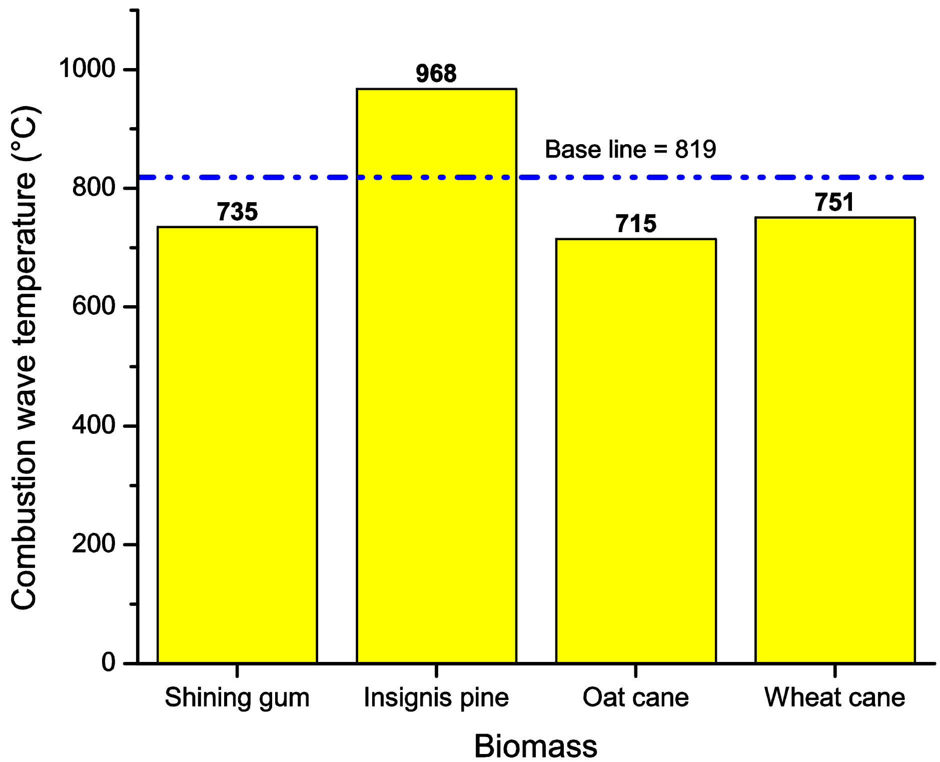
Fig. 7. Experimentally measured volumetric composition of products from hybrid filtration combustion of steam-air mixture and base lines for the biomass; A) Hydrogen, B) Carbon monoxide, C) Methane, D) Carbon dioxide.



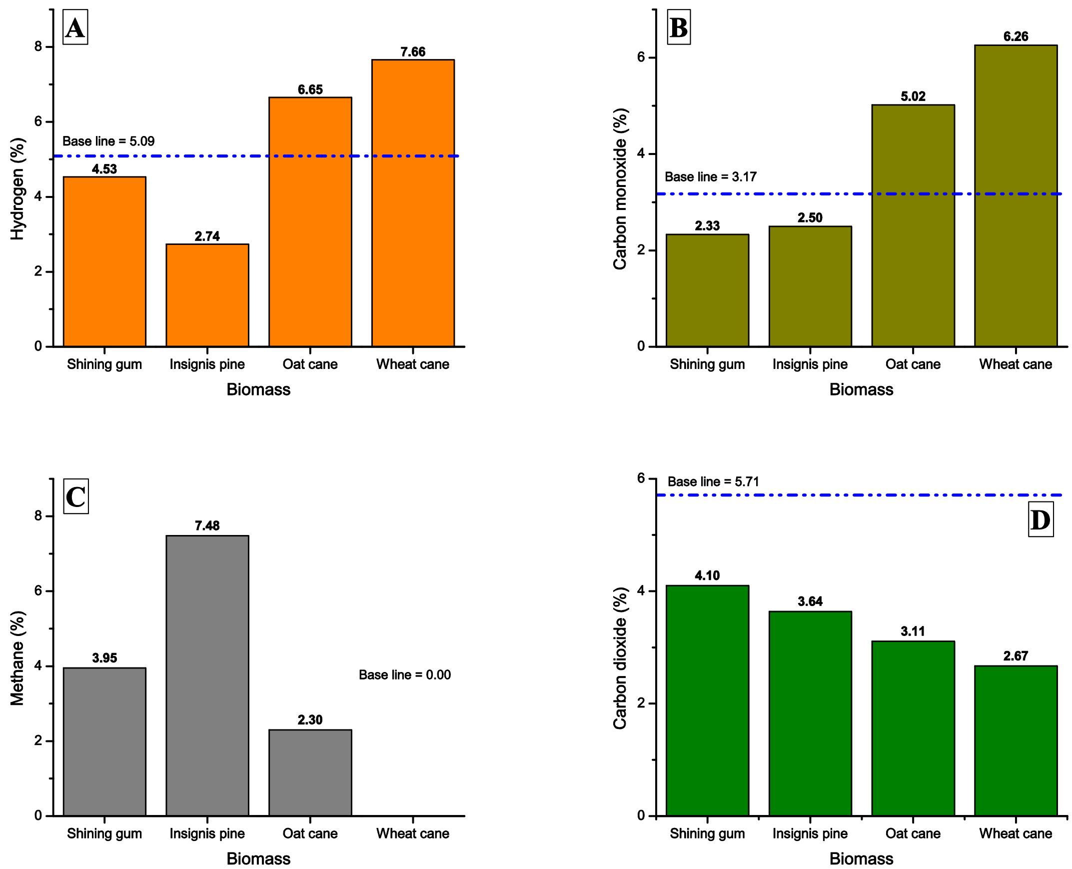
ϕ 46
ϕ 42
Thermal Insulation
S-type thermocouple
30
40
Inert zone 1
T1
T2
T3
T4
T5
T6
30
30
30
30
30
362
160
Hybrid zone
110
Inert zone 2
Flow direction
Mixing chamber
Air
Natural gas

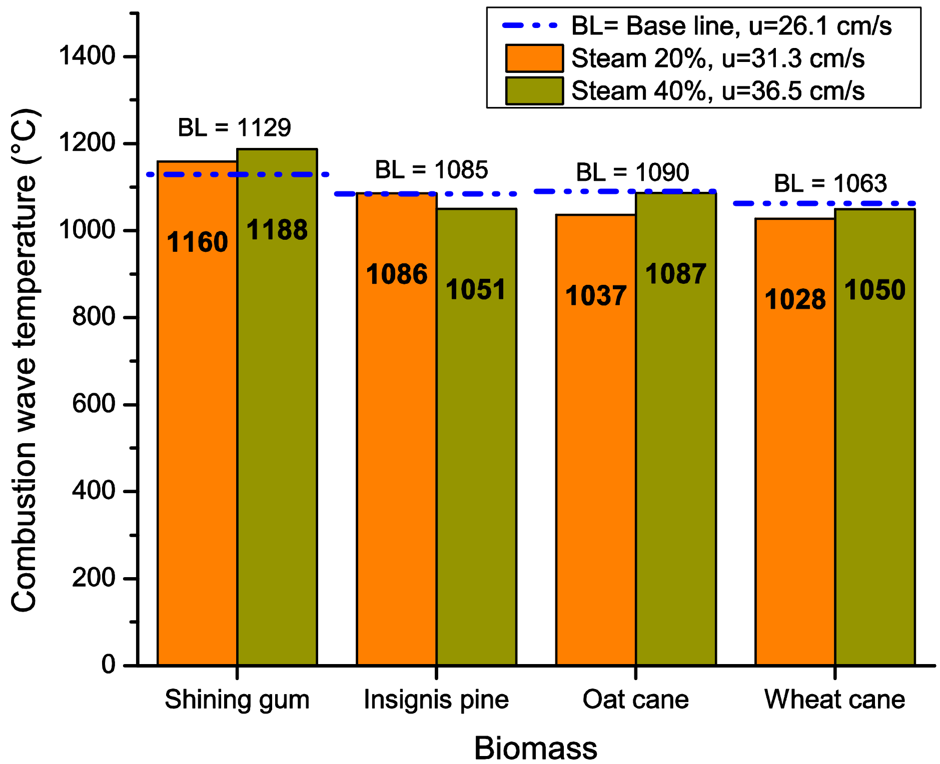


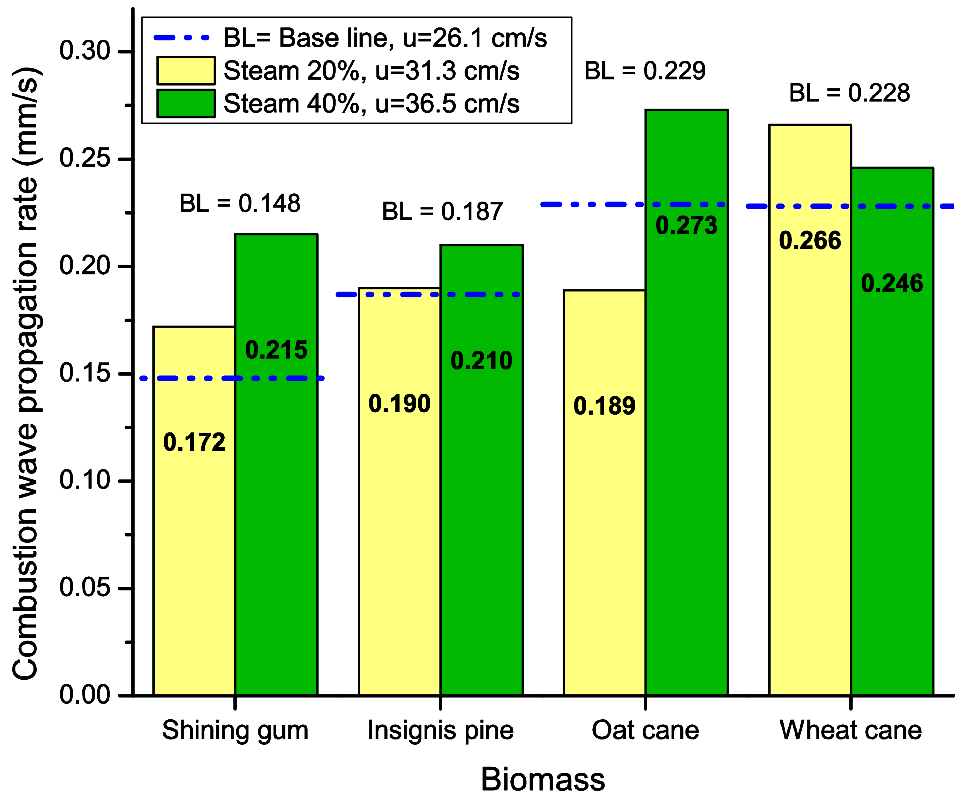
ϕ 46
ϕ 42
Thermal Insulation
S-type thermocouple
Inert zone 1
Hybrid zone
Inert zone 2
40
160
140
70
30
30
30
30
30
83
362
T1
T2
T3
T4
T5
T6
Flow direction
Mixing chamber
Copper tube ϕ 6
Air
Steam
Natural gas

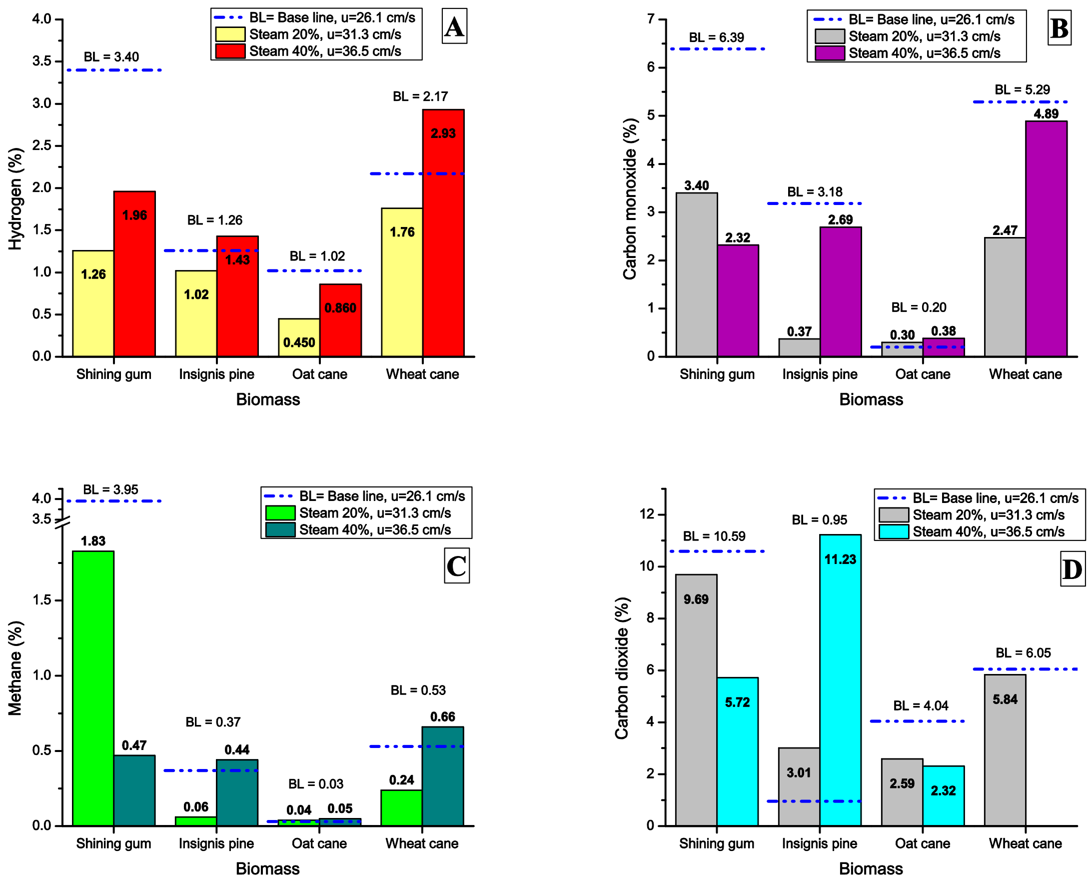


Combustion wave temperature (°C)
0
200
400
600
800
1000
968
Base line = 819
735
715
751
Shining gum
Insignis pine
Oat cane
Wheat cane
Biomass


A
Hydrogen (%)
Base line = 5.09
4.53
2.74
6.65
7.66
B
Carbon monoxide (%)
Base line = 3.17
2.33
2.50
5.02
6.26
C
Methane (%)
3.95
7.48
2.30
Base line = 0.00
D
Carbon dioxide (%)
Base line = 5.71
4.10
3.64
3.11
2.67
Shining gum
Insignis pine
Oat cane
Wheat cane
Biomass


BL= Base line, u=26.1 cm/s
Steam 20%, u=31.3 cm/s
Steam 40%, u=36.5 cm/s
BL = 1129
BL = 1085
BL = 1090
BL = 1063
1160
1188
1086
1051
1037
1087
1028
1050
Combustion wave temperature (°C)
0
200
400
600
800
1000
1200
1400
Shining gum
Insignis pine
Oat cane
Wheat cane
Biomass


BL= Base line, u=26.1 cm/s
Steam 20%, u=31.3 cm/s
Steam 40%, u=36.5 cm/s
BL = 0.148
BL = 0.187
BL = 0.229
BL = 0.228
0.172
0.215
0.190
0.210
0.189
0.273
0.266
0.246
Combustion wave propagation rate (mm/s)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Shining gum
Insignis pine
Oat cane
Wheat cane
Biomass


A
BL= Base line, u=26.1 cm/s
Steam 20%, u=31.3 cm/s
Steam 40%, u=36.5 cm/s
Hydrogen (%)
BL = 3.40
BL = 1.26
BL = 1.02
BL = 2.17
1.26
1.96
1.02
1.43
0.450
0.860
1.76
2.93
Shining gum
Insignis pine
Oat cane
Wheat cane
Biomass
B
Carbon monoxide (%)
BL = 6.39
BL = 3.18
BL = 0.20
BL = 5.29
3.40
2.32
0.37
2.69
0.30
0.38
2.47
4.89
C
Methane (%)
BL = 3.95
BL = 0.37
BL = 0.03
BL = 0.53
1.83
0.47
0.06
0.44
0.04
0.05
0.24
0.66
D
Carbon dioxide (%)
BL = 10.59
BL = 0.95
BL = 4.04
BL = 6.05
9.69
5.72
3.01
11.23
2.59
2.32
5.84