# EVALUATION AND SAFETY ASSESSMENT OF BIOMASS-/WASTE-GENERATED PRODUCER GAS

JAKUB ČESPIVA[1], JAN SKŘÍNSKÝ[1], JÁN VEREŠ[1], MAREK JADLOVEC[2],
JAN VÝTISK[2], TADEÁŠ OCHODEK[1] & STANISLAV HONUS[2]
[1]Centre for Energy and Environmental Technologies, Energy Research Centre,
VŠB – Technical University of Ostrava, Czech Republic
[2]Faculty of Mechanical Engineering, VŠB – Technical University of Ostrava, Czech Republic

## ABSTRACT

The production of synthetic gas and alternative liquid fuels, based on renewable and waste source materials, is an emerging topic. With growing energy demand and increasing $CO_2$ concentration within the atmosphere, caused by excessive fossil fuels combustion, alternative ways of energy utilisation, storage and transformation are intensely being sought and developed. Combining technologies of gasification and Fischer–Tropsch catalytic synthesis of biomass/waste materials can provide not only a possibility to replace fossil fuels extraction, but it can partially solve the issue of growing amounts of unprocessed waste materials. The 200 kW power input technology for gasification of biomass/waste materials with sliding bed, cross/updraft reactor was used to perform experimental measurements of conversion of waste materials into producer gas. This gas, with potential to be used as a source gas for catalytic synthesis was examined from quality and safety points of view. The composition and suitability for its utilisation was evaluated, as well as safety assessment in terms of its explosivity was determined. The latter mentioned was carried out in 1 $m^3$ spherical explosion vessel to determine pressure rise during the explosion of the producer gas. The results showed interesting differences between measured data and mathematical model, probably caused by the presence of other substances, such as tar compound, solid particles and other pollutants.

*Keywords: waste management, solid recovered fuel, gasification, sliding bed reactor, cross/updraft reactor, explosion parameters, explosion pressure 0.02 $m^3$ explosion vessel.*

## 1 INTRODUCTION

Today it is beyond doubt that our society heads towards fossil-free future. However, this noble errand may be difficult to achieve as alternative approaches are not as spread, reliable, and, in most cases, economically feasible. The energetic sector bears great responsibility in this matter and the implementation of alternative approaches is being very important in short time span. In general, it can be stated that around 84% of energy production comes from fossil resources worldwide, while only around 12% are a consequence of alternative energy sources implementation [1].

In terms of fuel, suitable for wide spectrum of subjects, including energetics and transportation, waste-based material could be a partial solution. Such material literally covers the whole planet, not excluding the uninhabited locations, unfortunately. The waste accumulation is then wrong for two chief reasons: (1) the environment suffers in vicinity of dangerous, decomposing and cumulating substances; and (2) valuable energy content is being wasted [2].

The more or less advanced technologies for sufficient energy from waste transformation exist around the globe, yet even in western world they do not satisfy the actual need, as the waste materials are produced in exceeding rate [2], [3]. For example, several studies that specify biomass-based waste utilization in small combustion applications for household heating were published. Unfortunately, these applications have very limited scope of use and do not solve the overall problem [4], [5]. Moreover, alternative ways of utilisation of this material are, to some extent, ignored. For instance, gasification of so called solid recovered

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fuel (SRF) has a potential to produce CO, $H_2$ and $CH_4$ rich producer gas which can be utilised in many ways without causing significant harm to the environment. The application of SRF into waste-to-liquid processes through gasification and Fischer–Tropsch catalytic synthesis can also present an interesting alternative for the future [6].

This study is aimed at evaluation of SRF-based gasification producer gas from energy and safety points of view. The second mentioned is very important consideration which must be done on the most precise level of determination. Safety of fuel materials in terms of their ignition and explosion characteristics must be studied prior handling such materials on industrial or household scale, because, producer gas is dangerous due to its content, combining poisonous and explosive compounds [7]. Several such determinations were made in the past.

Skřínský [8] and Skřínský et al. [9] studied the behaviour of biomass-derived producer gas within 0.2 $m^3$ spherical explosion vessel at various temperatures and pressures. Also, di Sarli et al. [10] studied similar gas from explosion point of view. He has determined wood chips-derived producer gas explosion pressures. Other works were published on this topic, however, none clearly determines such parameters for the producer gas made out of SRF gasification. Thus, determination of these parameters will be very important in near future, especially while SRF material represents quite a diverse mixture of materials [11], [12].

## 2 MATERIALS AND METHODS

### 2.1 SRF material

The very gasification process as well as the character and quality of the producer gas itself are strictly dependent on the input fuel. The character of the fuel can influence the process so much that some of its properties, such as moisture or heating value, may be limiting and can even make the performance impossible. Another important consideration would be the fuel granulometry. This parameter must be in accordance with the design of gasification reactor and its conveyors.

In this study, SRF, produced by OZO Ostrava company, Czech Republic, was used. It represents a mixture of materials collected in a vast location in and around Ostrava city, in form of sorted municipal and industrial non-recyclable wastes. An illustration of its main components is seen in Fig. 1 below, with the dominant compound being non-recyclable plastics and waste wood.

As mentioned above, the granulometry of the fuel must be suitable for the technology. The provided SRF was in the form of soft fluff with high bulk density equal to 109 $kg{\cdot}m^{-3}$ and grain size of 1–25 mm. From the fuel point of view, a very important factor is its calorific value, or, in other words, lower heating value (LHV). The LHV parameter determines energetic content within chemical bounds of the fuel. This is mostly affected by carbon and partially by hydrogen content. Other components, such as nitrogen, mineral compounds or non-flammable particles diminish the value of LHV, while others, such as sulphur (also enhances LHV), chlorine or mercury can even form environmentally hazardous substances, dangerous to the downstream technology and subsequent producer gas utilisation aggregates as well. Because of the safety reasons during combustion and transport of the fuel, the SRF material was mixed with basic wood pellets (LHV = 17.0 $MJ{\cdot}kg^{-1}$) in proportion of 3:2.

The results of proximate and ultimate analyses of SRF are summarised in Table 1.

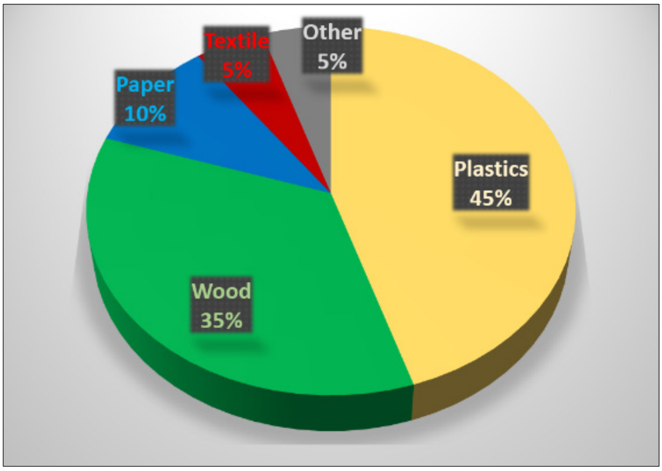

Figure 1: Illustrative composition of SRF.

Table 1: Proximate and ultimate analyses of SRF. All values in raw state.

| **Parameter** | **Symbol** | **Value** | **Unit** |
|---|---|---|---|
| Lower heating value | $LHV_f^r$ | 19.1 | $MJ \cdot kg^{-1}$ |
| Water | $W^r$ | 7.8 | % wt. |
| Ash | $A^r$ | 6.2 | % wt. |
| Carbon | $C^r$ | 48.8 | % wt. |
| Hydrogen | $H^r$ | 6.2 | % wt. |
| Oxygen | $O^r$ | 29.4 | % wt. |
| Nitrogen | $N^r$ | 1.6 | % wt. |
| Sulphur | $S^r$ | 0.1 | % wt. |
| Chlorine | $Cl^r$ | <0.4 | % wt. |
| Mercury | $Hg^r$ | <0.2 | $mg \cdot kg^{-1}$ |

## 2.2 Gasification process

The process of SRF gasification was performed on a pilot-scale unit of the Energy Research Centre, Centre for Energy and Environmental Technologies, VŠB – Technical University of Ostrava, Ostrava, Czech Republic. This technology is defined by a cross/updraft gasification reactor of 200 kW input power, equipped with sliding bed and circulating grate. Thus, the geometry of the reactor is designed so that fuel is lead from bottom to the grate area and gasification media (air) is brought to it by four tangential nozzles while producer gas is being sucked away in the upper part.

This reactor works in hybrid gasification/combustion regime in order to suffice the necessary temperature for thermochemical reactions (so called autothermal type). A pair of screw conveyors for fuel transportation are designed for materials of 10–30 mm size. The gasification air intake and producer gas outtake are realised by vacuum, caused by a suction fan, situated at the tail of the technology, behind cyclone barrier and moisture/tar condensers.

The sampling of the producer gas is being realised immediately at the reactor outlet, using a screwed sampling probe. The sampling track behind the probe is equipped with impinger bottles with propane-2-ol, immersed in cold bath environment of 4°C temperature, a suction pump, a flow meter, a gas analyser and an outlet for tedlar sampling bag. The analyser used for molecular composition determination in this study was GAS 3000p, Pollutek Gas Analysis, Belgium. This analyser is capable to determine percental (volume) content of the following gases: CO, $CO_2$, $CH_4$, $C_nH_m$ (dual beam infrared detector), $H_2$ (thermal conductivity detector) and $O_2$ (electrochemical detector) with 0.01% precision. The technology as well as the sampling track along with sampling methodology used are described in Češpiva et al. [6], [13], [14].

### 2.3 Explosion experiments

The producer gas explosion experiments were performed in a constant volume, stainless steel, double wall vessel of spherical shape (SN: 497-OZM-15, OZM Research, Czech Republic) adopted for the explosion experiments. This set-up consists of a 0.02 $m^3$ explosion vessel, heating system, spark generator and data acquisition system, closely described in Skřínský and Ochodek [15].

In order to reduce the number of experimental tests, preliminary thermodynamic and kinetic analyses were performed to predict the fuel–air equivalence ratio resulting in maximum pressure. Knowing the chemical equilibrium composition of the studied chemical system permits the calculation of theoretical, thermodynamic properties for the system. It was assumed that all gases are ideal and that interactions among phases may be neglected within the calculation. The calculation procedure was based on the minimization of free energy and was successfully tested for a similar gas composition in previous studies [16], [17].

The results of adiabatic explosion pressure calculations were used to predict the initial values for experimental producer gas/air measurement and were subsequently put in comparison to measured experimental results as obtained from the explosion vessel.

## 3 RESULTS AND DISCUSSION

### 3.1 Gasification process and producer gas quality

The process of gasification was performed in specific conditions in order to adjust the procedure for a unique fuel – SRF. The parameters within the reactor were defined by temperature $T = 955.5$ K and relative pressure $p = -0.2$ kPa ($p_{atm} = 99$ kPa). The consumption of the fuel $\dot{m}_f$ was equal to 40.4 $kg \cdot h^{-1}$ and the gasification air $\dot{V}_a$ equal to 10.4 $m^3h^{-1}$ in ambient temperature of 20°C. Such conditions defined the equivalence ratio $\lambda$ to be 0.2 with producer gas flow $\dot{V}_g$=73.3 $m^3 \cdot h^{-1}$. All values represent an hour average, during which the gasification process was performed and monitored. Parameters of the gasification process during experimental measurement, including gas composition as monitored at the sampling track, is evident in Table 2.

CGE being determined using:

$$\mathrm{CGE} = \frac{\dot{V}_g \cdot \rho_g \cdot LHV_g}{\dot{m}_f \cdot LHV_f}. \qquad \% \qquad (1)$$

The X value represents $N_2$ in majority. The sampling of the producer gas was done in stabile regime within the reactor and quasi-stable values of the gas components. The gas composition values given represent averages of 30 minutes of sampling. The producer gas was sampled at a rate of 60 $l \cdot h^{-1}$.

Table 2: Gasification process and producer gas parameters.

| **Parameter** | **Symbol** | **Value** | **Unit** |
|---|---|---|---|
| Temperature | $T$ | 950.5 | K |
| Relative pressure | $p$ | −0.2 | kPa |
| Fuel consumption | $\dot{m}_f$ | 40.4 | $kg\cdot h^{-1}$ |
| Air consumption | $\dot{V}_a$ | 10.4 | $m^3\cdot h^{-1}$ |
| Equivalence ratio | $\lambda$ | 0.2 | – |
| Cold gas efficiency | CGE | 30.4 | % |
| Producer gas flow | $\dot{V}_g$ | 73.3 | $m^3\cdot h^{-1}$ |
| Density | $\rho_g$ | 1.3 | $kg\cdot m^{-3}$ |
| Thermal capacity | $c_{p,g}$ | 1.3 | $kJ\cdot kg^{-1}\cdot K^{-1}$ |
| Lower heating value | $LHV_g$ | 3.2 | $MJ\cdot m^{-3}$ |
| Carbon monoxide | $CO$ | 10.0 | % vol. |
| Hydrogen | $H_2$ | 2.0 | % vol. |
| Methane | $CH_4$ | 5.1 | % vol. |
| Carbon dioxide | $CO_2$ | 13.6 | % vol. |
| Oxygen | $O_2$ | 1.3 | % vol. |
| Other | X | 68.0 | % vol. |

The SRF material was tested in fixed/sliding bed gasification reactors in other studies. Sobolewski et al. [18] examined SRF utilisation in laboratory-scale 60 kW installation. This updraft reactor was able to produce a gas with content of $CO$ = 8.6% vol., $H_2$ = 5.6% vol. and $CH_4$ = 2.5% vol. The LHV of this producer gas was equal to 4.3 $MJ\cdot m^{-3}$ [18], [19].

Al-Moftah et al. [20] has studied in his work the life cycle assessment (LCA) of SRF gasification in an updraft unit as alternative replacement for natural gas. The LCA analysis had shown very promising scenarios with positive environmental impact. Čespiva et al. [6] investigated SRF gasification before in similar technology with minor differences. Then, process conditions were defined as temperature 1073 K, pressure 0.1 kPa below atmospheric, fuel flow 9.4 $kg\cdot h^{-1}$ and producer gas flow 40 $m^3\cdot h^{-1}$. In conclusion, a total of 45.7 kg of alternative liquid fuel was produced out of a ton of SRF material through gasification and synthesis processes over Co catalyst.

### 3.2 Explosion experiments

A scenario of producer gas pipeline leakage can have fatal impact if mixed with air in vicinity of any energy initiator. The energy within the gas, which can be transformed into explosion, was examined. An experimental explosion vessel was filled with SRF producer gas, as described above, and mixed up with several air concentrations in order to determine maximum explosion pressure. The result of this analysis is depicted in the graph in Fig. 2. As is seen, five explosion tests were enough in order to achieve an explosion curve. The mathematical model in the graph has a high correlation index: $R^2 = 1$. The maximum explosion pressure $p_{ex}$ was determined to be in concentration of air equal to 9.6% vol. and its instantaneous value was 700 kPa.

In terms of explosive content of the producer gas, hydrogen is by far the most crucial parameter. The graph in Fig. 3 below describes the influence of different initial $H_2$ concentrations within producer gas on the explosion pressure and the pressure rise rate during

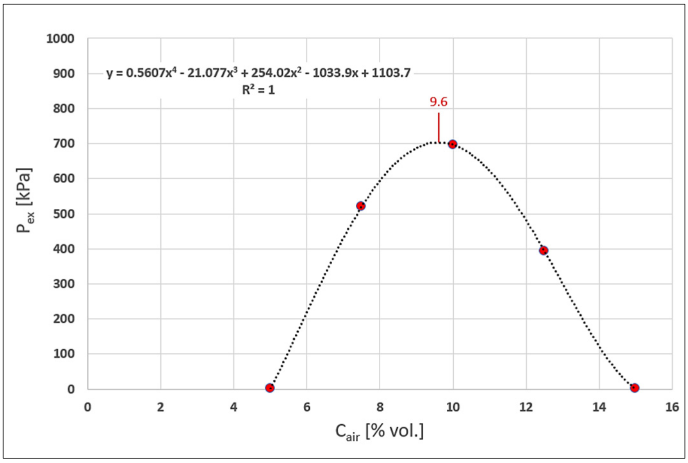

Figure 2: Pressure vs. concentration of air.

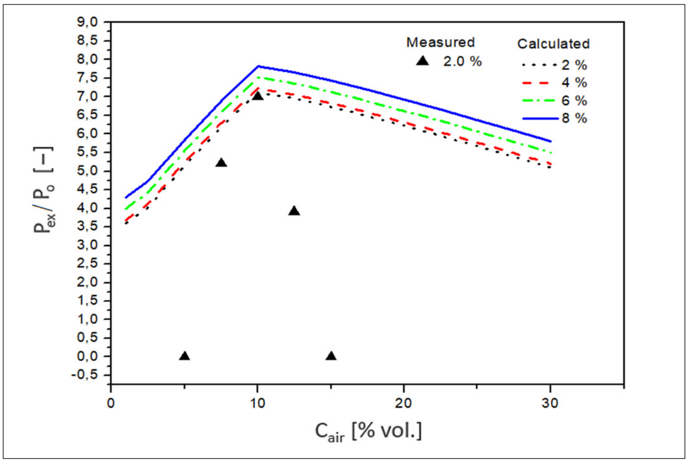

Figure 3: $P_{ex}/P_0$ vs. concentration for producer gas with 2–8 vol.% of $H_2$.

the explosion process. This graph followed a mathematical model, as described in Skřínský [8]. The explosion and adiabatic equilibrium pressure are normalized concerning the initial pressure ($p_0$ = 101 kPa).

The maximum explosion pressure and maximum rate of pressure rise are essential indicators for the evaluation of explosion energy distribution connected to environmental safety. The results of the detailed derivation show certain aspects of $H_2$ addition effects. A rough correlation with the explosion parameters is also apparent in terms of the pressure–concentration curve slope. The obtained results are crucial for exploring the role of $H_2$ content in the producer gas mixture.

Skřínský [8] studied the behaviour of biomass derived producer gas within 0.02 $m^3$ spherical explosion vessel and determined maximal pressure $p_{max}$ = 5.4–7.0 bar and deflagration index $K_G$ = 45–63 bar·m·$s^{-1}$ at various temperatures and pressures. Skřínský et al. [9] presented a study in which he found maximal explosion pressure $p_{ex} = 7.1 \pm 0.2$ bar and $K_G = 170 \pm 14$ bar·m·s$^{-1}$ for 30% vol. concentration of producer gas in air. This was achieved on the same 0.02 m$^3$ explosion vessel.

## 4 CONCLUSION

Alternative sources of energy are very likely to draw society's strong attention. Current anti-fossil trends are about to turn the focus on these alternatives, among which, gasification of waste-based materials will certainly achieve its share in the very near future.

In this experimental programme, producer gas derived from SRF material through the process of gasification was examined from quality and safety points of view. The stable gasification regime in sliding bed, cross/updraft reactor with 950.5 K ambient temperature was able to produce 73.3 m$^3$·h$^{-1}$ with simultaneous fuel consumption of 40.4 kg·h$^{-1}$. The energetic compounds of the gas were CO, $H_2$ and $CH_4$ in 10:2:5.1 volume rate. The lower heating value of the gas was equal to 3.2 MJ·m$^{-3}$.

The second part of the experiment included determination of maximal explosion pressure in different mixtures of the producer gas and air. The results showed $p_{ex}$ to be highest at a 9.6% vol concentration of the air. The value of $p_{ex}$ was in this case 700 kPa.

Before the SRF producer gas can be handled with safely in the industrial or local sphere, numerous experiments must be carried out in order to evaluate its potential dangers in the form of poisoning or exploding. This article summarises basic information and provides a basis for further research activities in this field.

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