The aim of this contribution is to evaluate the influence of calculated for various initial temperatures and pressures. rich H\(_2\) (in terms of bar(a)) of fuel lean, stoichiometric and fuel present contribution presents absolute explosion pressures the hazard associated with the reaction (CCPS, 1995). The tion can generate is one good measure of the magnitude of the maximum explosion pressure that the explosion reac external heat transfer may be inadequate. At the same time, cial iron a blast furnace gas (BFG) is produced as a “free” by-product (Vereš et al., 2011). The operation of such plants could be responsible for a significant number of accidents. The characteristic safety parameter of blast furnace gas in a closed vessel explosion, so called explosion characteristic, discussed in this contribution is the maximum explosion pressure. The maximum explosion pressure is the highest explosion pressure over the flammable range in a closed volume at a given fuel concentration (Eckhoff, 2005). These explosion characteristics are important for design of safety devices (e.g. relief systems, vents), able to ensure active protection of pressure vessels where flammable mixtures are formed. Beyond safety devices, the values of these parameters are useful for emergency management planning especially for developing scenarios where emergency relief or external heat transfer may be inadequate. At the same time, the maximum explosion pressure that the explosion reaction can generate is one good measure of the magnitude of the hazard associated with the reaction (CCPS, 1995). The present contribution presents absolute explosion pressures (in terms of bar(a)) of fuel lean, stoichiometric and fuel rich H\(_2/CO/CO_2/O_2/N_2\) blast furnace gas mixtures with air calculated for various initial temperatures and pressures. The aim of this contribution is to evaluate the influence of the temperature on the explosion parameters, namely maximum explosion pressure, of the blast furnace gas that is formed in the smelting operation. The primary outcomes are: explosion parameters at ambient conditions and elevated temperatures and pressures.

**Materials and methods**

Figure 1 gives the schematic view of the experimental setup. It is composed of ignition system, heating system, constant volume vessel, data acquisition system and inlet/exhaust system. The explosion vessel was equipped with a piezoelectric 10 bar pressure transducer connected to the data acquisition system for measuring the explosion data, a piezoelectric 2 bar pressure transducer to adjust the initial pressure, an ignition source and lines for evacuating the vessel, feeding the blast furnace gas/air mixture and exhausting the burned mixture. A series of induction sparks generated between stainless steel electrodes was used as an ignition source. The tips of the electrodes were positioned at the centre of the vessel. The distance between the tips was (5±0.1) mm. The mounting of the electrodes was resistant to the heat and pressure generated during the test and provided adequate electrical resistance from the test explosion vessel. A high voltage transformer (root mean square: 13–16 kV; short circuit current: 20–30 mA) was used for producing the series of ignition sparks. The blast furnace gas was metered by using a volumetric pump; the air was metered by using a mass-flow controller.
The explosion vessel and the mixing chamber were evacuated to a pressure 62 mbar, filled slowly with the gas and air mixture to 1 bar, purged by 2 times its volume and then, if necessary, the initial pressure was reduced again to the desired one. Before ignition, the mixture was allowed to become quiescent and thermally equilibrated (3–5 min). Care was taken not to warm up the equipment by explosions which were too frequent. The BFG–air mixtures were prepared by mixing together flows of air and BFG gas. The pressure measuring system (pressure transducer (Kistler), the amplifier (Kistler) and the recording system (Promotic)) fulfil the requirements of EN 13673-1 and EN 1839. Normally three tests for each composition were carried out except where the relative standard deviation is higher than that found with the test series of 6 tests performed. The mixture composition investigated and based on the real monitoring data is given in Table 1.

The mixture composition was obtained commercially in the form of pressurized bottles from SIAD and was used without further purification. The mixture was proven by analysing the flammable substance content for the test mixture and controlled by the portable GAS 3100R SYN-GAS Analyser (G.E.I.T. EUROPE, Belgium; SN: 112091). Test mixture lies within an uncertainty of measurement of ±10% relative for a flammable substance content up to 2 mol%, and +0.2% absolute for a flammable substance content above 2 mol% according to EN 13673-1. BFG–air mixtures with fuel concentrations between 30.0 and 40.0 vol.% (equivalence ratio between 0.54 and 2.26) were investigated at initial pressures ($p_0$) between 0.9 bar and 1.0 bar and initial temperatures between $T_0 = 298$ K and $T_0 = 308$ K.

Due to the complexity of the involved physical phenomena and to the lack of an adequate amount of reliable experimental data, a number of different models and calculation procedures for estimating the physical consequences following the physical explosion of a gaseous state are presently reported in the literature. Two computational approaches have been used for explosion pressure, Pad, calculations in this study. The element potential approach in the thermochemical equilibrium calculations applied in the Chemkin 3.6.2 subroutine using the species and their thermodynamic values from the GRI 3.0 and Konnov 5.0 (Pekalski et al., 2005) and the combustion equilibrium calculations by program GASEQ 0.79 obtained from the properties of the reactant species and of equilibrated adiabatic products using the species and their thermodynamic values from the Burcat.thr. Both chemical equilibrium models assumes adiabatic conditions in constant volume, and formation of equilibrium-defined concentrations of post explosion compounds and their expansion due to the temperature rise caused by the liberated heat assuming ideal gas behaviour. This approach represents ideal deflagrations in closed systems well and gives the highest possible

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>$H_2$</th>
<th>CO</th>
<th>$CO_2$</th>
<th>$N_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content vol. %</td>
<td>4.08±0.058</td>
<td>21.59±0.180</td>
<td>22.46±0.180</td>
<td>51.87±0.180</td>
</tr>
</tbody>
</table>
attainable explosion pressures. It has been shown that the model is able to predict, with a reasonable accuracy, the experimental values of the explosion pressures and constant volume adiabatic explosion temperatures also in different fuel-enriched conditions, for different types of gaseous explosions (Skrinsky et al., 2016a,b).

Results and discussion

Results of explosion experiments depend on many different parameters of the investigated process, such as the energy and type of ignition source, size and shape of explosion chamber, initial temperature, initial pressure and composition of the flammable mixture. To ensure the compatibility of data we selected the results for experiments that are in agreement with EN 13673-1. The results of theoretical predictions and experiments are summarized in Table 2–5.

A) Experimental and theoretical $P_{\text{max}}$ for $\text{H}_2/\text{CO}/\text{CO}_2/\text{O}_2/\text{N}_2$: at ambient temperature and pressure

Table 2 compares the theoretically derived data for the maximum explosion pressure of the studied blast furnace gas mixture components. The values were adopted from the databases as the IFA and the AiChE, and from the literature (EN 13673-1, 2003 and Yaws, 1999).

B) Theoretical $P_{\text{max}}$ for $\text{H}_2/\text{CO}/\text{CO}_2/\text{O}_2/\text{N}_2$: at elevated temperature and pressure

Computed adiabatic temperatures, $T_f$, and maximum explosion pressures, $p_{\text{max}}$, for blast furnace gas-air mixtures (15.0 vol. %, 35.0 vol. %, 55.0 vol. %, 75.0 vol. %) at various initial temperatures, $T_{\text{init}}$, and ambient initial pressure are given in Table 3 and Figure 2a,b. The values of uncertainty denotes the mean difference between the results of two computational approaches used in this study and is in agreement with (Pekalski et al., 2005).

From the numerical results of Table 3 it is possible to identify that the increase in the initial temperature lowers the maximum explosion pressure, and increases the flammability range of BFG/air mixture.

The value of the explosion pressure with varying $\text{H}_2/\text{CO}/\text{CO}_2/\text{O}_2/\text{N}_2$ concentration is similar at all investigated initial temperatures. The results of theoretical predictions and experiments are summarized in Table 2–5.

Results of explosion experiments depend on many different parameters of the investigated process, such as the energy and type of ignition source, size and shape of explosion chamber, initial temperature, initial pressure and composition of the flammable mixture. To ensure the compatibility of data we selected the results for experiments that are in agreement with EN 13673-1. The results of theoretical predictions and experiments are summarized in Table 2–5.
Fig. 2. Calculated explosion pressure vs fuel fraction for explosions of a) H$_2$/CO/CO$_2$/O$_2$/N$_2$ mixture with air at 298 K (top), 358 K (upper middle), 418 K (lower middle), and 478 K (bottom); b) H$_2$/CO/CO$_2$/O$_2$/N$_2$ with air mixture at 1 bar(a) (top), 5 bar(a) (upper middle), 10 bar(a) (lower middle), and 15 bar(a) (bottom)

Rys. 2. Obliczone ciśnienia wybuchu w zależności od udziału paliwa dla wybuchu a) dla mieszanki H$_2$/CO/CO$_2$/O$_2$/N$_2$ z powietrzem T0 = 298 K, 358 K (wyższa średnia), 418 K(niższa średnia) i 478K (dno); b) dla mieszanki H$_2$/CO/CO$_2$/O$_2$/N$_2$ z powietrzem 1 bar (a) góra, 5bar (a) wyższa średnia), 10 bar(a) niższa średnia i 15 bar (dno)

Fig. 3. Calculated explosion pressure vs initial temperature for explosions of a) H$_2$/CO/CO$_2$/O$_2$/N$_2$ mixture with air at 15.0 vol. % (top), 35.0 vol. % (upper middle), 55.0 vol. % (lower middle), and 75.0 vol. % (bottom); b) H$_2$/CO/CO$_2$/O$_2$/N$_2$ mixture with air at 1 bar(a) (top), 5 bar(a) (upper middle), 10 bar(a) (lower middle), and 15 bar(a) (bottom)

Rys. 3. Obliczone ciśnienie wybuchu w zależności od temperatury wybuchu dla; a) mieszaniny H$_2$/CO/CO$_2$/O$_2$/N$_2$ z powietrzem 15.0 vol. % (góra), 35.0 vol. % (wyższa średnia), 55.0 vol. % (niższa średnia) i 75.0 vol. % (dno); b) mieszaniny H$_2$/CO/CO$_2$/O$_2$/N$_2$ z powietrzem przy 1 bar(a) (góra), 5 bar(a) (wyższa średnia), 10 bar(a) (dolna średnia) i 15 bar(a) (dno)

Fig. 4. Results of flammability limits measurements for H$_2$/CO/CO$_2$/O$_2$/N$_2$ mixtures with air at T$_0$ = 298 K

Rys. 4. Wyniki pomiarów limitów palności dla mieszanin H$_2$/CO/CO$_2$/O$_2$/N$_2$ z powietrzem przy T$_0$ =298 K
good approximation at initial pressures i.e. up to 15 bar(a), but we may assume that will be increasing wrong at higher pressures.

C) Flammability limits of H\textsubscript{2}/CO/CO\textsubscript{2}/O\textsubscript{2}/N\textsubscript{2} mixtures with air at T\textsubscript{0} = 298 K

Previous studies on LEL and UEL are summarized in Table 5. From the data performed in Table 5, it is clear that the values of LEL are the same for H\textsubscript{2} but differs for CO (from 11.3–12.5 vol. %). The values of UEL for CO differs from 74.0–75.6 vol. %. In both cases is the value of UEL for CO behind the reproducibility of 0.2 vol. % required by EN 1839.

The values shown in Figure 4a,b are valid only for the conditions under which they were determined (room temperature and atmospheric pressure using a 1000-L explosion vessel with hot-wire ignition). Figure 5 illustrates the early stage (Figure 5a) and end (Figure 5b) of explosion (73.0 vol.% of H\textsubscript{2}/CO/CO\textsubscript{2}/O\textsubscript{2}/N\textsubscript{2} mixture with 27.0 vol. % of air at T\textsubscript{0} = 298 K). In both photos the characteristic vortex closed to the ignition point in the middle of the vessel is observed. Because the concentration is very close to the upper explosion limit, the flame front could be observed and is not destroyed by the pressure increase.

Conclusion

The adiabatic explosion pressures of H\textsubscript{2}/CO/CO\textsubscript{2}/O\textsubscript{2}/N\textsubscript{2} mixture with air at various initial temperatures and pressures were calculated together with the measurements of LEL and UEL. The model predictions for the blast furnace gas mixtures are compared for four different initial temperatures. Although the results from the evaluation indicate that presented theoretical simulations can become a valuable tool for rough estimation, the modelling requires further improvements to be useful for consequence modelling and design of industrial facilities. Thus, at the first stage, the equilibrium calculations can be used as a rough calculation of a worst case scenario. At the same time, these values could be used as initial values for further explosion experiments carried out in heated 1 m\textsuperscript{3} explosion apparatus designed by OZM Research s.r.o. at Energy Research Centre, VŠB - Technical University of Ostrava. As the practical outcome these results will apply for the iron making processes, where iron ore is reduced with coke into metallic iron and the explosive BFG is formed. The results represents a continuation of numerous efforts by various research groups, where the key underlying problem has been the understanding of results obtained in laboratory tests for predicting the consequences of multicomponent gas mixture explosion scenarios in industry (Skrinsky et al., 2015).

Acknowledgements

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Charakterystyka wybuchowa gazu wielkopiecowego

Celem artykułu jest charakterystyka i zagrożenia wynikające z wybuchu gazu wielkopiecowego. Niebezpieczeństwo pożaru i wybuchu wywodzone jest przez łatwopalne składniki gazu wielkopiecowego. Aby zapobiec wybuchom w trakcie powstawania gazu wielkopiecowego konieczne jest poznanie granic wybuchowości poszczególnych składników gazu i mieszanin gazowych z powietrzem. Gaz wielkopiecowy z różnych wielkich pieców może się znacznie różnić pod względem składu. W związku z tym, dla każdego składu gazu należy określić granice wybuchowości. Wymaga to znacznego czasu i wysiłku. Z tego powodu granice wybuchu gazu wielkopiecowego są często określone (w literaturze dotyczącej bezpieczności) tylko przez zawartość frakcji wodorowej w mieszaninie gazowej. W rzeczywistości gaz wielkopiecowy składa się z wodoru, tlenku węgla, dwutlenku węgla i innych gazów resztkowych. Granice wybuchowości są generalnie przekroczone.

Słowa kluczowe: maksymalne ciśnienie wybuchu, stała objętość, temperatura adiabatyczna, gaz wielkopiecowy