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**PROPERTIES OF ARTIFICIAL GASEOUS MIXTURES FOR THEIR SAFE USE AND SUPPORT  
THE NATURAL GAS SUPPLY NETWORKS****WŁASNOŚCI SZTUCZNYCH MIESZANIN GAZOWYCH DO BEZPIECZNEGO ICH UŻYTKOWANIA  
I WSPOMAGANIA ZASILANIA SIECI GAZU ZIEMNEGO**

The increase in natural gas consumption by the general public and industry development, in particular the petrochemical and chemical industries, has made increasing the world interest in using gas replacement for natural gas, both as mixtures of flammable gases and gas mixtures as LPG with air (SNG – Synthetic Natural Gas). Economic analysis in many cases prove that to ensure interchangeability of gas would cost less than the increase in pipeline capacity to deliver the same quantity of natural gas. In addition, SNG systems and installations, could be considered as investments to improve security and flexibility of gas supply. Known existing methods for determining the interchangeability of gases in gas gear based on Wobbe index, which determines the heat input and the burning rate tide, which in turn is related to flame stability. Exceeding the Wobbe index of a value increases the amount of carbon monoxide in the exhaust than the permissible concentration. Methods of determining the interchangeability of gases is characterized by a gas in relation to the above-described phenomena by means of quantitative indicators, or using diagrams interchangeability, where the gas is characterized by the position of a point in a coordinate system. The best known method for determining the interchangeability of gases is Delbourg method, in which the gas is characterized by the revised (expanded) Wobbe Index ( $Wr$ ), the combustion potential, rate of soot formation ( $I_{ch}$ ) and the ratio of the formation of yellow ends ( $I_j$ ). Universal way to determine the interchangeability of gas is also Weaver accounting method. It does not require determination of the reference gas. It is designed for utensils for household gas and gas pressure  $p = 1.25$  kPa.

The criteria and definition of gas interchangeability volatility in practice to the combustion in a gas gear. In the case of gas exchange in industrial furnaces, interchangeability criteria are usually not very useful because of other conditions of combustion and heat exchange. In industrial reheating furnace gas is combusted in a sealed combustion chambers. Air supply is regulated. The exhaust gases are discharged into canals and the chimney to the atmosphere. The temperature difference between load (fuel gas) and the flame is much less than in the case of gas household appliances. In the furnace heat exchange takes place mainly by radiation in 85% to 95%. The value of heat flux flowing from the gas to a heated charge is not proportional to the heat load burners. Interchangeability of gas is linked by adding to natural gas, a certain amount of gas that is a substitute for natural gas in meeting the criteria for substitution in order to ensure certainty of supply of natural gas to customers. Gases that can be used in the processes of blending and used as replacement gases are mainly a mixture of propane and propane – butane (LPG – Liquid Petroleum Gas), landfill gas or biogas (LFG – Landfill Gas) and dimethyl ether (DME). One

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of the more well-known gas mixtures used in many countries around the world to compensate for peak demands is a mixture containing about 75% of natural gas and approximately 25% propane / air (LPG / air). Also in Poland is prepared to amend the provisions in this regard (at this moment – oxygen in the gas network can not exceed 0.2%).

In this paper, the calculations of interchangeability of gas mixtures LFG – LPG and LPG – air (SNG) for natural gas was made. It was determined whether the analyzed mixtures have similar stable flame zones regardless of the quality of LFG fuel and whether they may in whole or in part replace CH<sub>4</sub>, without any modification of equipment suction air for combustion. The obtained results will determine whether the fuel can be used as a replacement for natural gas used in such household appliances and, possibly, industrial burners. In connection with the possibility of changes in the quality of LFG, depending on such factors as storage time, as pre-treatment, will be determined the degree of interchangeability of LFG as a fuel mixed with regard to its quality.

**Keywords:** Natural gas, interchangeability of gases, burning velocity, peak shaving, Liquid Petroleum Gas, propane, Landfill Gas, Wobbe Index

Wzrost zużycia gazu ziemnego przez odbiorców komunalnych oraz rozwój przemysłu w szczególności petrochemicznego i chemicznego sprawił, że na całym świecie wzrosło zainteresowanie zastosowaniem gazów zamiennych za gaz ziemny, zarówno jako mieszanin gazów palnych jak i jako mieszanin gazów płynnych z powietrzem (SNG – syntetyczny gaz ziemny). Przeprowadzane analizy ekonomiczne w wielu przypadkach dowodzą, że zapewnienie wymienności paliwa gazowego kosztowało by mniej niż zwiększenie przepustowości gazociągów dla dostarczenia tej samej ilości gazu ziemnego. Ponadto systemy i instalacje SNG, można by uznać za inwestycje poprawiające bezpieczeństwo i elastyczność dostaw gazu.

Znane dotychczasowe metody określania zamienności gazów w przyborach gazowych oparte są na liczbie Wobbego, która decyduje o obciążeniu cieplnym przyboru i szybkości spalania, z którą z kolei związana jest stabilność płomienia. Przekroczenie liczby Wobbego o pewną wartość powoduje wzrost ilości tlenku węgla w spalinach ponad dopuszczalne stężenie. Sposoby określające wymiennosc gazów charakteryzują dany gaz w odniesieniu do opisanych wyżej zjawisk przy pomocy wskaźników liczbowych lub za pomocą diagramów wymiennosci, na których gaz jest scharakteryzowany przez położenie punktu w układzie współrzędnych. Najbardziej znaną metodą określenia zamiennosci gazów jest metoda Delbourga, w której gaz scharakteryzowany jest przez skorygowaną (rozszerzoną) liczbę Wobbego ( $W_r$ ), potencjał spalania, współczynnik tworzenia się sadzy ( $I_{ch}$ ) oraz współczynnik powstawania żółtych końców ( $I_f$ ). Uniwersalnym sposobem określenia zamiennosci gazu jest również metoda rachunkowa Weavera. Nie wymaga ona określenia gazu odniesienia. Przeznaczona jest dla przyborów gazowych użytku domowego i ciśnienia gazu  $p = 1,25$  kPa. Kryteria zmienności gazów i definicja zamiennosci w praktyce dotyczy spalania gazów w przyborach gazowych. W przypadku wymiany gazu w piecach przemysłowych kryteria zmienności są zazwyczaj mało przydatne z powodu innych warunków spalania i wymiany ciepła. W przemysłowych piecach grzewczych gaz spala się w zamkniętych komorach spalania. Dopływ powietrza jest regulowany. Spaliny odprowadzane są kanałami i kominem do atmosfery. Różnica temperatur nagrzewanego wsadu (paliwa gazowego) i płomienia jest dużo mniejsza niż w przypadku przyborów gazowych domowego użytku. W piecach wymiana ciepła odbywa się głównie przez promieniowanie w 85% do 95%. Wartość strumienia cieplnego płynącego od gazu do ogrzewanego wsadu nie jest proporcjonalne do obciążenia cieplnego palników.

Zamiennosc gazów związana jest dodawaniem do gazu ziemnego pewnej ilości gazu będącego substytutem naturalnego gazu ziemnego przy spełnieniu kryteriów zmienności w celu zagwarantowania pewności dostaw gazu ziemnego do odbiorców. Gazy mogące być użyte w procesach mieszania i wykorzystane jako gazy zamiennie to przede wszystkim propan lub mieszaniny propan – butan (LPG – z j. ang. *Liquid Petroleum Gas*), gazy wysypiskowe lub biogazy (LFG – z j. ang. *Landfill Gas*) oraz eter dimetylowy (DME). Jedną z bardziej znanych mieszanek gazowych stosowanych w wielu krajach świata do wyrównywania szczytowych zapotrzebowań jest mieszanka zawierająca ok. 75% gazu ziemnego i ok. 25% mieszanki propan / powietrze, (LPG / air). Również w Polsce przygotowywana jest zmiana przepisów w tym względzie (obecnie zawartość tlenu w sieci gazowej nie może przekraczać 0,2 %).

W artykule przeprowadzono obliczenia zamienności mieszanin paliw gazowych LFG – LPG i LPG – powietrze (SNG) za gaz ziemny. Określono czy analizowane mieszaniny mają podobne stabilne strefy płomienia niezależnie od jakości LFG i czy paliwa te mogą w pełni lub w części zastąpić  $\text{CH}_4$ , bez żadnych modyfikacji urządzeń zasysających powietrze do spalania. Uzyskane wyniki, pozwolą stwierdzić, czy paliwa te mogą być wykorzystane jako zamienne za gaz ziemny użytkowany we wspomnianych urządzeniach gospodarstwa domowego i ewentualnie palnikach przemysłowych. W związku z możliwością zmian jakości LFG w zależności od takich czynników jak czas składowania, sposób obróbki wstępnej, zostanie określony również stopień wymienności LFG jako paliwa mieszanego w odniesieniu do jego jakości.

**Słowa kluczowe:** Gaz ziemny, zamienność gazów, szybkość spalania, szczytowe zapotrzebowanie, gaz płynny, propan, biogaz, liczba Wobbe’go

## Index

$H_s$	– gross calorific value (GCV).
$H_i$	– net calorific value (NCV).
$W_s$	– Wobbe index.
$d$	– relative density.
$S_L$	– laminar burning velocity.
$\Phi$	– mixture concentration ratio.
$K_G$	– explosion index.
$P_{\max}$	– maximum pressure of explosion.
$(dP/dt)_{\max}$	– maximum increase of explosion pressure.
$P_i, P_k$	– initial and final pressure, respectively.
$t_d$	– ignition delay.
$t_s$	– total combustion time.

With the increasing gas consumption, gas industry stays responsible for gas production, transport and storing but not always and not everywhere can fully satisfy the end consumer’s needs for this fuel. When the gaseous fuel is supplied to the gas networks, peak demands, especially local and short-term ones, can be made by the construction and operation of the so-called satellite installations re-gasifying liquid natural gas (LNG) or through gaseous mixtures. This however necessitates re-dimensioning of gas network at the stage of designing or later reconstruction works have to be done to increase its capacity (Nagy, Olajossy, Siemek, 2004; Łaciak 2009). The unused increased capacity of pipelines beyond the peak demand obviously increases the cost of exploitation of the network.

The economic case analyses prove that providing interchangeability of gaseous fuel would bring greater economic effect than increasing the capacity of gas pipelines providing the same amount of natural gas. Moreover, the synthetic natural gas (SNG) systems and installations can be considered to be investments which can improve the safety and flexibility of gas deliveries.

As is known the gross calorific value (GCV) and net calorific value (NCV) characterize the amount of heat energy, which can be obtained from a unit of natural gas in the process of combustion. Those parameters can be used for calculating energy provided to the end customer with the received portion of gas. Another important parameter depending on gross calorific value ( $H_s$ ) and relative density ( $d$ ) of gas is the Wobbe index,  $W_s = H_s/\sqrt{d}$ .

The upper and the lower Wobbe figures decide about whether or not gas can be efficiently used in the gas receiver with nominal heat load. The concentration of the main hydrocarbon

components (aliphatic hydrocarbons from  $C_1$  to  $C_{6+}$ ) is the parameter on the basis of which  $H_s$ ,  $H_i$ , compressibility coefficient, divisor and dividend of Wobbe index can be calculated. Those calculations also require knowing the composition of hydrocarbon fraction  $C_6$  as well as composition of hydrogen and non-combustible components of natural gas, i.e. nitrogen, carbon dioxide, helium, argon, oxygen, etc.

Knowing the aromatics, mercury vapours and sulphur compounds contents one can evaluate whether or not the using of gas by individual and industrial users is safe for human health and the environment.

The interchangeability of gases is related with admixing a certain amount of gas, which is a substitute of natural gas, meeting the interchangeability criteria, in order to guarantee the safety of gas deliveries to the customer. Gases which can be used in the process of mixing and used as interchangeable gases are mainly propane or propane-butane mixtures (Liquid Petroleum Gas – LPG), landfill gas and biogas (Landfill Gas – LFG) and in certain conditions di-methyl ether (DME), (Marchionna, 2008).

One of the best known gaseous mixtures applied in numerous countries all over the world for balancing peak demands is a mixture containing ca. 75% natural gas and ca. 25% propane-butane (LPG/air) mixture.

Already known methods of determining gas interchangeability for specific gas appliances are mainly based on the Wobbe index, which determines the heat load of the appliance, combustion rate, and which is related with the stability of combustion. The issue of threatened natural gas deliveries necessitates adding gaseous mixtures to the gaseous networks, however neither causing any qualitative changes in the distributed gas nor having any negative impact on the security of the users, (Eaton, 2005; Laciak, 2011). In a number of countries the LPG-air mixtures are applied. Polish regulations are about to be changed; presently, (PN-C-04752: 2002) the oxygen content in the gas network cannot exceed 0.2%. However, introduction of those changes will require investigating the process of mixing and analyzing safety of use of gaseous mixtures.

A number of industrial processes employing gaseous fuels are run uninterruptedly. Any break in fuel deliveries may result in stopping the production and consecutively, considerable economic losses. Such companies are frequently required to have an alternative source of energy in case the energy deficiency situation appears. This can assume the form of systems for mixing propane and air, i.e. systems producing synthetic liquid gas (SNG) as a counterpart of natural gas. Opposite to diesel fuel, furnace oil or propane, SNG does not require any additional gas appliances, pipelines, regulators, or special fuel reception systems.

Another cheap renewable energy source is the landfill gas (LFG) generated spontaneously or produced (biogas) from organic matter. After cleaning and treating, the gas could be interchanged with natural gas in the combustion processes for domestic and industrial purposes (Lee, Hwang, Lee 2008).

Gases acquired from new sources do not burn properly in the presently existing gas installations, although their properties meet the standards, or reversely, the can be well combusted even though they do not meet the standards. Therefore, new criteria of gas evaluation and interchangeability have been worked out.

It has been assumed that gases interchange among themselves if they well burn in the same appliances and in the same conditions, at the same pressure and when the following conditions are satisfied:

- Heat load of gas appliance remains unchanged. Gas composition and also amount of sucked primary air have influence on the above conditions. This condition can be also

fulfilled if the Wobbe index for both gases has the same value, with admissible allowance  $\pm 5.0\%$ .

- The flame is stable, does not have any tendency to sever or counter-flow into the burner. The stability of flame depends on the maximum rate of gas burning and air suction coefficient. With its growth, the flame is less stable.
- Combustion should be complete. The carbon dioxide content in waste gases should not exceed admissible values. Partial combustion manifests itself in the presence of carbon oxide in waste gases and yellow-ended flames. Admissible carbon oxide content in undiluted waste gases is  $0.1 \div 0.05$  vol.%. The limit value for the gas is also established with the use of carbon monoxide to carbon dioxide ratio, which should not exceed 0.01.

The ways of determining interchangeability of gases are characteristic of a given gas in reference to above described phenomena with the use of figure data or interchangeability diagrams, for which the gas has been characterized (position of a point in the coordinates system).

The Delbourg method is the best known method for determining gas interchangeability, where gas has been characterized by:

- corrected (extended) Wobbe index,
- combustion potential,  $D$ ,
- soot formation coefficient,  $I_{ch}$ ,
- coefficient of yellow-ended flames formation,  $I_j$ . The two last coefficients depend on the hydrocarbons content in gas.

The gas interchangeability can be also defined in a universal way by the Weaver calculation method. It does not require defining any reference gas. This method is fit for domestic gas appliances and gas pressure  $p = 1.25$  kPa. The interchangeability is determined by calculating six indices for two gases, where one of them is the reference gas. If the listed interchangeability indices, two of which:

- refer to heat load of gas appliance,
- have stabilization of flame,
- the quality of combustion, i.e. soot and carbon oxide formation and

their values stay within values given by Weaver, then gases are mutually interchangeable.

Weaver indices:

- interchangeability index for heat load –  $I_H$
- interchangeability index for sucked primary air –  $I_A$
- interchangeability index for counter-flow flame  $I_F$  – interchangeability index for flame severing –  $I_L$
- interchangeability index for carbon monoxide formation –  $I_I$  – interchangeability index for yellow-ended flame formation –  $I_Y$

In practice the gas interchangeability criteria and definition of interchangeability refers to gas combustion in gas appliances. When gas is exchanged in industrial furnaces, the interchangeability criteria are of little use because of different combustion conditions and heat exchange. In industrial furnaces gas is combusted in closed combustion chambers. The airflow is regulated. The waste gases are discharged through canals and chimney to the atmosphere. The temperature differences of heated charge (gaseous fuel) and flames are much lower than in the case of do-

mestic gaseous appliances. In 85% to 95% of cases the heat exchange in furnaces mainly takes place through radiation. The heat stream flowing from gas to the heated charge is not proportional to the heat load of the burners. Heat from radiation increases nearly proportionally to the 4<sup>th</sup> power of temperature of the source of radiation. The calorimetric temperature of combustion of gas supplied to the furnace has an influence on the result of the heating process, (Grzybczyk, Laciak, Grela, 2011).

## Landfill Gas (LFG)

A number of papers on the use of LFG, both in the form of biogases and landfill gases can be found in literature. In the case of landfill gases, it is generated by anaerobic decomposition of municipal solid waste (MSW) in landfills and mainly consists of methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) as well as minor quantities of nitrogen and oxygen, and also traces of volatile organic compounds (VOCs). Recently, the use of LFG has raised considerable interest as an alternative energy source for heat, electric energy and fuels production. The LFG production usually begins immediately after opening the MSW landfill, to reach its top production after about 10 years, and lasting for about 40 years or longer. Another source of LFG can be biogases generated in biogas plants. The quality of LFG as a fuel increases with the growing CH<sub>4</sub> content and its composition may considerably differ, depending on the type of landfill, time elapsed, preprocessing method, etc. The net calorific value of LFG usually ranges from 12.56 to 25.12 MJ/m<sub>n</sub><sup>3</sup>, which is enough for it to be used as fuel in various heating systems, though the mixing methods may differ, depending on the quality of LFG.

The investigations, which have been described in literature focused mainly on the influence of CO<sub>2</sub> content in LFG on the combustion rate, contraction of combustibility and explosiveness limits as well as the emission of contaminations.

Qin et al. (2001) performed complex fundamental and environmental investigations of LFG use for energy generation. In their studies Lee et al. (2008) proposed new correlations of determining combustion rate of LFG and LFG – LPG as a function of equivalence ratio. They revealed that the CO<sub>2</sub> content in LFG causes that heat losses increase through radiation in low flames with simultaneous lowering of NO<sub>x</sub> emission. Lee and Hwang (2007) investigated the stability of flames when combusting LFG/LPG mixtures in domestic appliances and industrial turbulent-jet burners without pre-mixing of gas and air. Various gaseous mixtures were analyzed; they were so selected as to reach the Wobbe index ( $W_s$ ) and net calorific value ( $H_i$ ) equivalent to the respective values typical of natural gas (group E). The required values of LFG, being a component of the analyzed gaseous mixtures, were obtained by selecting contents of CH<sub>4</sub> from 55 vol.% to 30 vol.% in the mixture making up LFG. The basic properties of fuels were obtained by comparing the temperature of the flame, combustion rate and stability of combustion. The purpose of the study was to check out whether the mixtures had similar flame stability zones regardless the LFG quality or if the fuels could fully substitute CH<sub>4</sub>, without necessary modifications of the air suction elements used for the combustion process.

The temperature profile of flames of mixed fuels turned out to be similar to that of pure CH<sub>4</sub>. Although LFG contains about 45% of neutral gases, i.e. CO<sub>2</sub> and N<sub>2</sub>, relatively high flame temperatures were obtained, i.e. about 1900 K. The thermodynamic calculations and the obtained calculation results reveal that both the combustion rate and stability of flames confirmed that

the LFG/LPG mixtures could be used interchangeably with natural gas without any changes in the gas burning appliances.

In experiments, presented in literature, special attention was paid to defining basic properties of combustible mixtures, i.e. laminar rate of burning, minimum ignition energy, delayed ignitions, combustibility boundaries and extinction diameters.

## Synthetic Natural Gas (SNG)

The propane-air mixtures (known as LPG-Air or SNG), are the synthetic natural gas which was created by mixing vapor of LPG with air, most frequently about 45% of air and about 55% of gas (LPG or propane, mixture concentration ratio  $\Phi = 1.22$ ). After mixing up, we had a homogeneous mixture which could be used as a substitute of natural gas (to 25% of gas stream) in the combustion processes, e.g. to regulate peak demands.

Defining burning velocity as one of the basic tasks related with the possibility of interchanging gaseous fuels, propane/air and LPG/air. The usability of propane and LPG as components of mixtures used as interchangeables was analyzed by, e.g. Huzayyin et al. (2007). The author addressed the problem of changes in the laminar burning velocity ( $S_L$ ) and determining the so-called "explosion index" ( $K_G$ ) of LPG/air and propane/air mixtures in a wide range of mixture concentration ratio ( $\Phi = 0.7-2.2$ ), initial temperature ( $T_i = 295-400$  K) and pressure ( $P_i = 50-400$  kPa). For this reason a cylinder pressure tank ("bomb") was construed for further experiments. The combustion rate was defined with the use of a number of models, depending on the changes of pressure ( $P-t$ ) of the combustion process at minimum ignition energy. The explosion index  $K_G$  was constant for a given mixture or for specific components of the mixture. Dahoea et al. (2003) give a simple dependence for  $K_G$ :

$$K_G = (dP/dt)_{\max} V^{1/3} = (36\pi)^{1/3} (P_k - P_i) \left(\frac{P_k}{P_i}\right)^{1/T} S_L \quad (1)$$

where  $(dP/dt)_{\max}$  is maximum rate of growth of explosion rate,  $P_i$  and  $P_k$  are initial and final pressure, respectively.

On the basis of their investigation, Huzayyin et al. (2007) give a new equation for combustion rate ( $S_L$ ) of LPG/air mixtures in the form:

$$S_L = S_{LO} (T/T_n)^\alpha (P/P_n)^\beta \quad (2)$$

where:

$$S_{LO} = 1209.1 \Phi - 935.5 \Phi^2 + 708.1 \Phi^3 - 229.0 \Phi^4 - 492.8 \quad (3)$$

$$\alpha = 275.0 \Phi - 2.13 \Phi^2 + 2.0 \quad (4)$$

$$\beta = 0.029 \Phi - 0.026 \Phi^2 - 0.137 \quad (5)$$

$P_n$  and  $T_n$  are pressure and temperature in normal conditions.

Exemplary changes of combustion rate  $S_L$  in a function of pressure and temperature in reference to eqs. (2-5) for various values of  $\Phi$  have been presented in figs. 1 and 2.

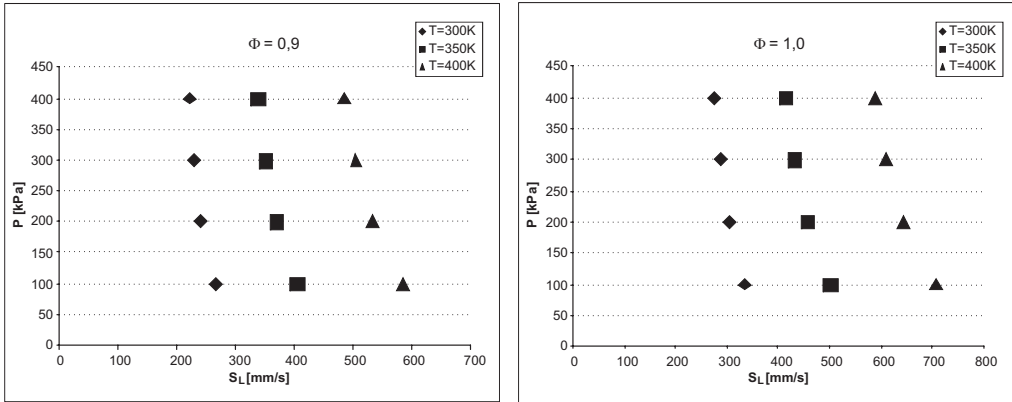


Fig. 1. Burning velocity  $S_L$  depending on pressure and temperature ( $\Phi = 0.9$  and  $1.0$ )

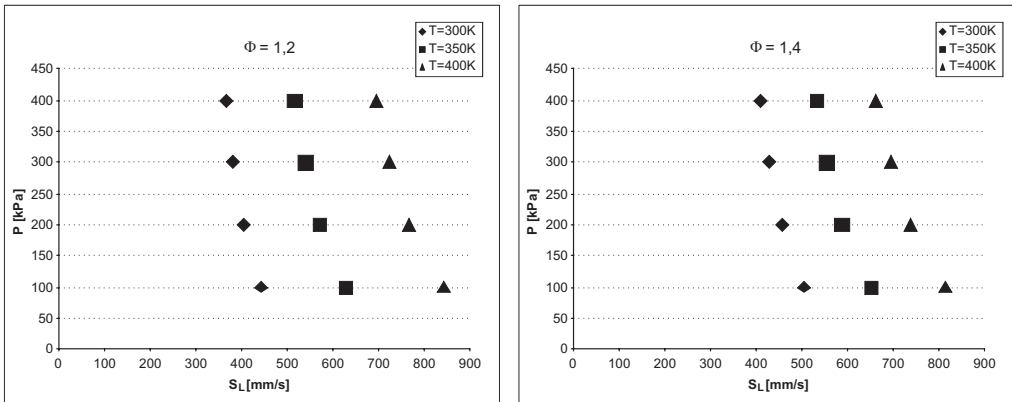


Fig. 2. Burning velocity  $S_L$  depending on pressure and temperature ( $\Phi = 1.2$  i  $1.4$ )

In another model construed on the basis of Dahoea et al. (2003) the following formulae were proposed for calculating the burning velocity in a function of pressure:

$$X = \frac{P - P_i}{P_e - P_i}; \quad r_b = r \left( 1 - \frac{P_i T_u P_e - P_i}{P T_i P_e - P_i} \right)^{1/3} \quad (6)$$

$$S_L = \frac{r}{3} \left( \frac{P_i}{P} \right)^{\frac{1}{T_u}} \frac{1}{(P_e - P_i)} \left[ 1 - \left( \frac{P_i}{P} \right)^{\frac{1}{T_u}} \left( \frac{P_e - P}{P_e - P_i} \right) \right]^{-\frac{2}{3}} \frac{dP}{dt} \quad (7)$$



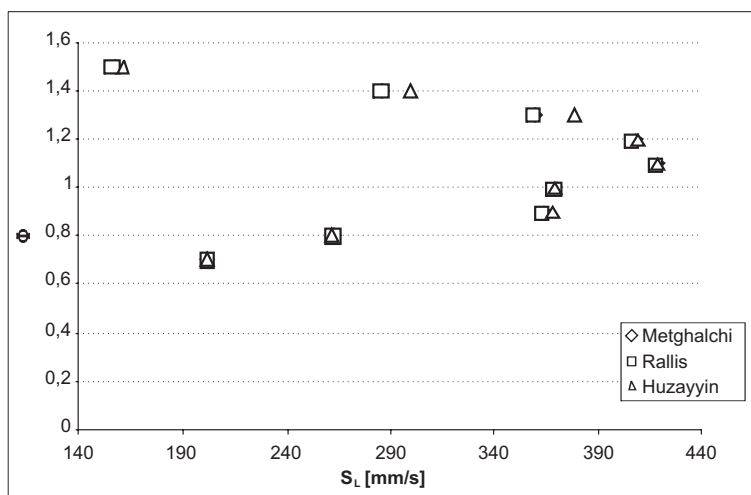


Fig. 3. Comparison of burning velocity  $S_L$  vs. coefficient  $\Phi$  for propane/air mixtures in normal conditions according to models by: Metghalchi & Keck, Rallis & Huzayyin et al.

The analysis of experiments for various models, e.g. Huzayyin et al. (2007) and earlier Metghalchi & Keck (1980) reveals that the maximum laminar burning velocity  $S_L$  for propane equals to 455 mm/s at  $\Phi = 1.1$ , whereas for LPG it is 432 mm/s ( $\Phi \approx 1.5$ ). In nearly all researches the value of  $S_L$  for propane/air mixture at  $\Phi = 1.0$  equals to about 415 mm/s. The explosion index ( $K_G$ ) can be also calculated on the basis of laminar burning velocity ( $S_L$ ) which is 93 bar m/s for propane and almost 88 bar m/s for LPG, fig. (2-5).

The maximum pressure of explosion  $P_{\max}$ , maximum rate with which explosion pressure grows  $(dP/dt)_{\max}$ , ignition delay ( $t_d$ ) and total combustion time ( $t_s$ ) greatly depend on the type of the gaseous fuel and coefficient  $\Phi$ . The course of changes remains similar, therefore:

- For a given  $\Phi$  value within the combustion limits, in the case of propane/air mixtures the flame is spreading faster than in LPG/air mixtures, which can be indicated by relatively higher  $P_{\max}$ ,  $(dP/dt)_{\max}$  values at lower ignition delay  $t_d$  and combustion time  $t_s$  values. The  $\Phi$  value, corresponding to the maximum rate with which flame moves, is lower ( $\Phi = 1.2$ ) for the propane-air mixture than for LPG-air mixture ( $\Phi = 1.5$ ). The differences are related with the structure of hydrocarbon molecules (length of chains and chain branchings) Glassman (1996).
- In both types of mixtures the maximum value of burning velocity is reached for mixtures richer in fuel. This is related with the necessity to compensate for the effect of hydrocarbons dissociation at higher temperatures.
- The closer to the explosion limits, the lower are the combustion rates. At the „poor“ side ( $\Phi < 1$ ), part of the liberated energy is lost because of the excessive air; this leads to lowering of  $P_{\max}$  and  $(dP/dt)_{\max}$  values, and increase of  $t_d$  and  $t_s$  values. At the opposite side ( $\Phi > 1$ ) the oxygen deficiency causes incomplete combustion, and so reduced the reaction of oxidation.

- With the increase of initial pressure of mixture  $P_i$  the combustion rate  $S_L$  decreases for both fuels, and grows with the increase of the initial temperature  $T_i$ .
- The maximum  $\text{NO}_x$  emission is nearly the same for both mixtures, though appears at various concentrations: for propane/air mixtures at the level of a poor mixture ( $\Phi \approx 0.9$ ) and for LPG/air at the level of a rich mixture ( $\Phi = 1.2$ ).

Determining the explosion parameters of mixtures it can be said that for low initial values of pressure  $P_i$  the maximum explosion pressure  $P_{\max}$  for propane mixtures reaches higher values than for LPG mixtures. With the increase of pressure  $P_i$  the situation changes and  $P_{\max}$  grows for LPG mixtures. The maximum value of explosion pressure increase  $(dP/dt)_{\max}$  for propane is about 20% higher than for LPG (depending on composition). The importance of the growth of explosion pressure  $K_G$  is definitely much bigger than the influence of the growth of initial temperature  $T_i$ .

Those and other results would indicate propane as more fit for interchangeability processes than LPG. Undoubtedly, one of the reasons is the lack of butane (a component of LPG) which has a considerably higher specific weight, hindering proper mixing of gases.

## Conclusions

- (a) The propane (LPG)-air mixtures (known as LPG-Air or SNG) can be used as a direct substitute of natural gas in the combustion processes, e.g. for regulating peak demands in proper proportions and concentration.
- (b) One of the cheapest renewable energy sources is LFG which is generated spontaneously (landfill gas) or produced (biogas) from organic matter. The net calorific value of LFG usually ranges between 12.56 and 25.12 MJ/m<sub>n</sub><sup>3</sup>.
- (c) Adiabatic temperatures of flames for all types LFG/LPG mixtures are very similar to temperature profiles of CH<sub>4</sub>, though the temperatures drop down with the decreasing percentage of CH<sub>4</sub> in the LFG mixture.
- (d) Maximum burning velocity of mixed fuels decreases linearly with the drop of CH<sub>4</sub> content in LFG. However, even in the case of a mixture with LFG containing about 70% of neutral gases, the measurements of burning velocities reveal that it can be used in any combustion system.
- (e) Most of LFG/LPG mixtures have very similar stable flame zones, and regardless the quality of LFG can completely substitute CH<sub>4</sub> without having to modify the gaseous appliances.
- (f) The stability of flame zone of mixtures decreases with the drop of CH<sub>4</sub> content in LFG. The LFG/LPG mixture can substitute CH<sub>4</sub> entirely or with some limitations covering, e.g. regulation of burner sucking the air.
- (g) The maximum rate of laminar burning velocity ( $S_L$ ) for propane-air mixtures is 455 mm/s at  $\Phi = 1.1$  and 432 mm/s for LPG/air mixtures ( $\Phi \approx 1.5$ ).
- (h) The maximum increase of explosion rate  $(dP/dt)_{\max}$  for propane is about 20% higher than for LPG, whereas the maximum explosion pressure  $P_{\max}$  at higher initial pressures  $P_i$  is higher for LPG.
- (i) Better results in all gas interchangeability experiments have been obtained when low- or zero-butane LPG mixtures were used (technical propane as LPG).

- (j) The difference of density (specific weight) of components of gaseous mixtures used for gas interchangeability processes may constitute a significant problem in certain conditions, sometimes neglected at the stage of designing.
- (k) Experimental admixing di-methyl ether (DME) directly to the low-pressure gas networks gave positive results. DME as gaseous fuel has numerous advantages: considerably lowers ignition temperature of DME/natural gas mixture (lower activation energy), improves combustion efficiency, lowers the temperature of flame – lower NO<sub>x</sub> emission. Among other advantages, besides methane interchangeability, are easy transport and safety of deliveries.
- (l) The first and basic criterion of gas interchangeability remains the constant Wobbe index ( $\pm 5.0\%$ ).

## References

- Eaton G.D. 2005. *Peak Shaving with Synthetic Natural Gas*. Ely Energy.
- Grzybczyk B., Łaciak M., Grela I., 2011. *Energetyka gazowa. Obsługa i eksploatacja urządzeń i sieci*. Wyd. Tarbonus. Tarnobrzeg-Kraków.
- Glassman I., 1996. *Combustion* (3<sup>rd</sup> ed.). Academic Press. San Diego.
- Huzayyin A.S., Moneib H.A., Shehatta M.S., Attia A.M.A., 2008. *Laminar burning velocity and explosion index of LPG – air and propane – air mixtures*. Fuel 87.
- Halchuk R.A., 2001. *Gas Quality Specifications and Interchangeability for End Use Applications*. AGA Operations Conference. Dallas. TX.
- Johnson F., Rue D.M., 2002. *Gas interchangeability tests: Evaluating the range of interchangeability of vaporized LNG and natural gas*. Final Report. Gas Research Institute. GRI-03/0519.
- Łaciak M. i in., 2011. *Instalacje i sieci gazowe*. Wyd. Verlag Dąshofer, Warszawa.
- Łaciak M., 2011. *Analiza możliwości zamienności i zmian jakościowych gazów w aspekcie bezpiecznego użytkowania i wspomaganie zasilania sieci gazu ziemnego z zastosowaniem równoważnych mieszanin gazowych*. Zeszyty Naukowe AGH Wiertnictwo. Nafta. Gaz, t. 28, z. 1-2.
- Łaciak M., 2009. *Ocena niepewności wyników statycznej symulacji sieci gazowych*. Zeszyty Naukowe AGH Wiertnictwo, Nafta, Gaz, t. 26, z. 4.
- Lee C.E., Hwang C.H., Lee H.Y., 2008. *A study on the interchangeability of LFG-LPG mixed fuels with LFG quality in domestic combustion appliances*. Fuel 87.
- Lee C.E., Hwang C.H., 2007. *An experimental study on the flame stability of LFG and LFG-mixed fuels*. Fuel 86.
- Lee C.E., Oh C.B., Jung I.S., Park J., 2002. *A study on the determination of burning velocities of LFG and LFG – mixed fuels*. Fuel 81.
- Lee C.E., Lee S.R., Han J.W., Park J., 2001. *Numerical study on effect of CO<sub>2</sub> addition in flame structure and NO<sub>x</sub> formation of CH<sub>4</sub> – air counter flow diffusion flames*. Int. J. Energy Res., 25.
- Metghalchi M., Keck J.C., 1980. *Burning velocity of propane – air mixtures at high temperature and pressure*. Combust Flame. 38.
- Marchionna M., Patrini R., Sanfilippo D., Migliavacca G., 2008. *Fundamental investigations on di-methyl ether (DME) as LPG substitute or make-up for domestic uses*. Fuel Processing Technology, Vol. 89, Issue 12.
- Nagy S., Olajosy A., Siemek J., 2004. *Analysis of Usefulness of Some Algorithms for Steady State Simulation in the Loop Gas Networks*. Archives of Mining Sciences, Vol. 49, No 2.
- Qin W., Egolfopoulos F.N., Tsotsis T.T., 2001. *Fundamental and environment aspects of landfill gas utilization for power generation*. Chem. Eng. J. 82.

- Qin W., Egolfopoulos F.N., Tsotsis T.T., 1999. *A detailed study of the combustion characteristics of landfill gas*. WSS/CI 1999 Fall Meeting 1999:99F-033.
- Rallis C.J., Garforth A.M., 1980. *The determination of laminar burning velocity*. Prog. Energy & Combust. Sci., 6.
- Ruffcorn S., Feinberg K., 2001. *Propane – air standby systems: gas energy uninterrupted*. EsMagazine.
- Technical Report Page 5.1 Title: 2007. Annual Technical Report to TransCanada PipeLines Ltd. TR 2103 5.0 Gas Interchangeability Program. NOVA Chemicals. (2007).
- Williams T.A., 2006. *Technical background and Issues of Gas Interchangeability*. AGA Staff Paper.
- White Paper on Natural Gas Interchangeability and Non-Combustion End Use. NGC+ Interchangeability Work Group. February 28. (2005).
- PN-C-04752:2002 Gaz ziemny. Jakość gazu w sieci przesyłowej.
- PN-C-04753:2002 Gaz ziemny. Jakość gazu dostarczanego odbiorcom z sieci rozdzielczej.

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