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## Replacing conventional fuels in USA, Europe, and UK with plastic pyrolysis gases – Part II: Multi-index interchangeability methods

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## ABSTRACT

The global increase in natural gas (NG) consumption and its steady decline in availability have spurred the search for new or alternative energy sources, such as pyrolysis gases. This article examines whether it is possible to burn pyrolysis gases from common plastic wastes in conventional burners without any adjustment to burner design. To determine the interchangeability of individual gases, several multi-index methods applicable to combustion devices in Europe, the USA, and the UK were used. This report is a continuation of a previous article (Part I) discussing the results of graphical methods for determining interchangeability. Similar to Part I, the results here imply that poly(vinyl chloride) (PVC) gases produced at a minimum of 700 °C have the highest replacement potential, and gases produced by polystyrene (PS) pyrolysis at 900 °C also conform with replacement requirements. For plastics mixtures, gases generated by pyrolysis at a minimum of 700 °C would be suitable alternatives to NG. These findings may contribute to plastic waste reduction as well as the discussion of reducing NG consumption. There is significant potential for follow-up research in this area, because the replacement of conventional fuels with gases obtained from wastes has not yet been sufficiently explored.

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### 1. Introduction

This article is directly related to Part I, which examined the potential for replacing conventional fuels (natural gas (NG) and propane) with gases produced in the pyrolysis of major polymers and their mixtures. Based on 24 experiments examining the pyrolysis of poly(ethylene terephthalate) (PET), polypropylene (PP), polyethylene (PE), poly(vinyl chloride) (PVC), polystyrene (PS), and 3 mixtures of these materials at 500, 700, and 900 °C, the interchangeability of the individual gases was examined via five methods that focused on the ability of the gases to maintain the combustion stability and heating rate of the combustion devices.

The introduction in Part I summarized the current global situation with regards to the accumulation of plastic wastes. Subsequently, the use of plastic waste pyrolysis gases in combustion devices was proposed for reducing waste volumes and evaluated in terms of interchangeability. Apart from the potential for reducing waste volumes and use in energy production, a major motivation for discussing interchangeability is the increasing global demand and simultaneous depletion of domestic

NG sources [1–3]. Precisely predicting when the global deposits of NG will be depleted is not possible; however, based on studies by Lior and BP Global as well as calculations by Shafiee and Topal [4–6], depletion is estimated to occur in 2066, 2068, and 2042, respectively. Further estimates based on information about NG deposits in various countries/parts of the world, particularly North America, Europe (including Eurasia), and Asia have projected that these deposits will be depleted by 2027, 2072, and 2043, respectively [7]. The future use of NG that is found trapped within shale formations (shale gas) remains a subject of considerable debate in the literature, with various opinions ranging from highly optimistic [8] to less so [9]. In the context of growing consumption even add that natural gas has the potential for next unconventional used [10–14].

Due to the dependence of leading economies on NG [15] as well as its important properties and limited deposits [16–18], the use of alternative energy sources is vital for meeting the ever-growing global demand for energy without considerably disrupting the energy supply [19].

The problem of the inevitable depletion of natural gas is the main motivation for our research. Although several literature sources have considered NG replacement from various technical perspectives, a comprehensive evaluation of its substitution by

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## Nomenclature

$b_{Dg}$	parameter which signifies the tendencies in individual hydrocarbons to the production of soot	$WN$	Wobbe number, $(MJ\ m_N^{-3})$
$C_{(K)}$	Knoy index, $(Btu\ ft^{-3})$	$Y$	AGA factor which reflects the potential for yellow tipping
$d$	relative density		
$E_{PN}$	equivalent mixture $C_3H_8 + N_2$ , (%)		
$F$	AGA coefficient		
$\dot{H}_S$	heat of combustion, $(MJ\ m_N^{-3})$		
$ICF_{(D)}$	incomplete combustion factor		
$I_{C(D)}$	Delbourg soot index		
$I_{F(AGA)}$	AGA flashback index		
$I_{J(D)}$	Delbourg yellow tipping index		
$I_{L(AGA)}$	AGA lifting index		
$I_{Y(AGA)}$	AGA yellow tipping index		
$J_{A(W)}$	Weaver air supply index		
$j_{Dg}$	coefficient which describes the susceptibility of individual hydrocarbon flames to yellow tipping		
$J_{F(W)}$	Weaver flashback index		
$J_{H(W)}$	Weaver heat rate index		
$J_{I(W)}$	Weaver incomplete combustion index		
$J_{L(W)}$	Weaver lifting index		
$J_{Y(W)}$	Weaver yellow tipping index		
$K$	AGA coefficient, which relates to the combustion velocity		
$L_{(D)}$	lift index		
$N_C$	sum of atoms of carbon		
$R_{H/C}$	ratio of hydrogen to carbon atoms contained in the fuel		
$SI_{(D)}$	soot index		
$S_{L,N}$	maximum combustion speed, $(cm\ s^{-1})$		
$T$	minimum quantity of air that is necessary for removal of yellow tipping, $(m_N^3\ m_N^{-3})$		
$V_t$	stoichiometric volume of combustion air, $(m_N^3\ m_N^{-3})$		
		<b>Subscripts</b>	
		$i$	component $i$
		$s$	replacement gas index
		$a$	replaced gas index
		<b>Greek symbols</b>	
		$\Omega$	volumetric fraction, $(\%_{vol.})$
		<b>Abbreviations</b>	
		AGA	American Gas Association
		BB	Bio-fermenter biogas
		CNG	compressed natural gas
		EU m.	EU mix
		JP m.	Japan mix
		LB	landfill biogas
		LNG	liquefied natural gas
		LPG	liquefied petroleum gas
		NG	natural gas
		NGC	Natural Gas Council
		OSG	offshore gas
		PE	polyethylene
		PET	poly(ethylene terephthalate)
		PNG	piped natural gas
		PP	polypropylene
		PS	polystyrene
		PVC	poly(vinyl chloride)
		US m.	USA mix

pyrolysis gases generated from plastic wastes that originate in various locations has not been published. This article describes the application of four interchangeability methods, with a special focus on the so-called “multi-index” methods. (This article also presents a single one-index method, Knoy’s method.) Based on the results of these methods, the potential for using 24 pyrolysis gases as a substitute for NG can be predicted. The Weaver multi-index method developed in the USA involves six interchangeability indices reflecting the heating rate of the gas, the feed of combustion air, as well as lifting, flashback, incomplete combustion, and yellow tipping after the interchange of two gases [20]. The American Gas Association (AGA) has also studied the undesired phenomena that may occur on interchanging two gases, and their results were initially published in Research Bulletin No. 36 [21]. Similar to Weaver’s method, the AGA method also reflects the dynamics and specific properties of flame, particularly the degree of “yellowness,” lifting, and flashback, which are 3 interchangeability indices. The combination of both series of the aforementioned indices (Weaver and AGA) was used in subsequent AGA *Interchangeability Programmes* in 1988, 2001, and 2002 [21]. In 2005, the Natural Gas Council (NGC), of which the AGA is a part, published interim instructions for evaluating gas quality based on information in the relevant literature on the composition of gases in the USA and the aforementioned interchangeability methods. These instructions confirmed the topicality of these methods [22].

In the 1980s, B.C. Dutton from British Gas designed three indices for the evaluation of interchangeability in Great Britain: incomplete combustion factor, the lifting index, and the soot index. These indices are currently also recognized in Australia [23–25].

Another work worth mentioning is that of Knoy, which offered an early method for determining the interchangeability degree (and was not included in Part I). The author introduced the interchangeability coefficient, according to which calorific power and specific density are major factors in gas interchange [26]. The Knoy coefficient has consequently become an equivalent of the Wobbe number ( $WN$ ).

The recent literature provides only a limited number of publications focused on interchangeability evaluation in terms of maintaining flame stability and use of the aforementioned multi-index methods. Related studies have investigated, for example, the combustion stability of 11 gases (3 types of piped natural gas (PNG), 2 types of offshore gas (OSG) and 6 types of liquefied natural gas (LNG)) in 16 groups of low-pressure burners used in China [27]; the interchangeability of 2 types of landfill gas and liquefied petroleum gas (LFG + LPG) mixtures in domestic gas appliances through a comparison of flame temperature, combustion velocity, and combustion stability [28]; flame stability after interchanging PNG and LNG, primarily in terms of the degree of yellow tipping, lifting, and combustion velocity [29]; the combustion of landfill biogas (LB) and bio-fermenter biogas (BB) from municipal waste in a common natural gas- or LPG-fired kitchen range [30]; flame stability for six types of biogases on a reference testing burner with various outlet diameters [31]; and compressed natural gas (CNG) premix flame stability in a Bunsen burner with two different outlet diameters [32].

This article examines the interchangeability of conventional gases and plastic pyrolysis gases primarily using the above-described multi-index methods, which predict the probability of

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