



Influence of water vapour and tar compound on laminar flame speed of gasified biomass gas

Nur Farizan Munajat^{*}, Catharina Erlich¹, Reza Fakhrai², Torsten H. Fransson³

Department of Energy Technology, School of Industrial Technology and Management (ITM), Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden

ARTICLE INFO

Article history:

Received 6 January 2012

Received in revised form 21 February 2012

Accepted 4 March 2012

Available online 27 April 2012

Keywords:

Gasified biomass gas

Laminar flame speed

Water vapour

Benzene vapour

ABSTRACT

Biomass can be converted to a gaseous fuel through gasification in order to be used in higher efficiency conversion equipment. Combustion of a gaseous fuel generally allows for higher combustion temperatures than that of a solid fuel leading to the higher efficiency. However, the gasified biomass gas (GBG) contains condensable compounds, such as water vapour and tars, which both will affect the subsequent combustion process with respect to emission levels and flame stability. Cleaning of the GBG prior to combustion is very costly and therefore further research is needed on direct combustion of GBG containing these condensable compounds, in order to develop stable combustion techniques for GBG. The laminar flame speed is a main parameter that relates to other important flame properties such as stability, extinction limit and flashback. Each of GBG components have different chemical and transport properties, which then influences the laminar flame speed of GBG. In this study, the individual effect of water vapour (H_2O) and tar compound addition in simulated GBG on laminar flame speed is investigated at atmospheric pressure. The tar compound used is benzene (C_6H_6) and simulated GBG used is $CO/H_2/CH_4/CO_2/N_2$ mixture. Experiments were carried out with conical burner stabilized flame and a Schlieren photography system. The volume fraction of additives in the fuel mixture was varied: for H_2O from 0% to 5% and for C_6H_6 from 0% to 10%. The unburned fuel air mixture was preheated and the temperature was maintained at $T_i = 398$ K to avoid condensation of the liquid. It was found that measured laminar flame speed of GBG–air mixture decreases with addition of H_2O in the fuel mixture. While, non-monotonic behaviour is shown with addition of C_6H_6 . Initially, as the volume fraction of C_6H_6 incremented, the laminar flame speed decreases, reaching a minimum value, and then increase.

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1. Introduction

Biomass gasification has been proven as an option of high efficiency energy conversion and diverse in end-use applications. For heat and/or power generation, combustion of gasified biomass gas (GBG) in gas engines or gas turbines potentially reduces the CO_2 emission compared to natural gas and diminishes the dependence of fossil fuels. Apart from these advantages, the drawback with GBG is the presence of tar occurring in a real gasification process and which been identified as one of the main challenges in the development of combustion devices.

Similar to the major gas composition of GBG, tar originating from biomass gasification also depends heavily on the gasification process parameters: gasification agent (air, steam, and oxygen),

biomass feedstock and gasifier type. It was reported that the average tar content in GBG can range from 0.5 g/Nm³ in a downdraft gasifier to 50 g/Nm³ in an updraft gasifier [1]. For circulating fluidized beds, the average tar content is 8 g/Nm³ and in the bubbling type, 12 g/Nm³, all values given for gasification of wood in air [1]. However, often only low tar amount is accepted for end-use applications of the GBG. Milne et al. [2] summarized tar tolerance limits for various GBG's applications, i.e. less than 50 – 500 mg/Nm³ for compressors, 50 – 100 mg/Nm³ for internal combustion engines, and 5 mg/Nm³ for direct-firing in gas turbines. The existence of these tolerance limits are caused by following reasons: (i). at ambient temperature, tars may condense and result in plugging and corrosion in downstream process equipment, pipes and combustion devices and (ii). tars also represent an energy loss, leads to reduction in overall efficiency of the gasification conversion processes. Therefore, tars in the GBG have always been considered as one of the main barriers that hindered application of biomass gasification and its integrated system at full-scale operation.

Up to now, varying methods and technologies have been developed to tackle the tar problems. A recent example is the utilization of catalyst material in a gasifier which can convert tars into H_2 and

^{*} Corresponding author. Tel.: +46 8 790 74 67; fax: +46 8 20 41 61.

E-mail addresses: munajat@energy.kth.se (N.F. Munajat), erlich@energy.kth.se (C. Erlich), reza.fakhrai@energy.kth.se (R. Fakhrai), fransson@energy.kth.se (T.H. Fransson).

¹ Tel.: +46 8 790 74 68; fax: +46 8 20 41 61.

² Tel.: +46 8 790 74 29; fax: +46 8 20 41 61.

³ Tel.: +46 8 790 74 75; fax: +46 8 20 41 61.

Nomenclature

A_b	surface area of burned flame, m^2	S_b	flame speed of burned mixture, m/s
c_p	specific heat, J/kg·K	T_a	overall activation temperature, K
D	mass diffusivity, m^2/s	T_i	initial reactant temperature K
ER	equivalence ratio	ρ_u	density of unburned mixture, kg/m^3
f	stoichiometric fuel/air ratio	ρ_b	density of burned mixture, kg/m^3
h	height of conical flame, m	\dot{m}	mass flow rate of the unburned mixture, kg/s
k	thermal conductivity, W/m·K	\dot{v}	volumetric flow of the unburned mixture, m^3/s
Le	Lewis number	ρ	density, kg/m^3
r	radius of conical flame, m	χ	volume fraction, %
S_u	flame speed of unburned mixture, m/s	α	thermal diffusivity, m^2/s

CO, hence improving the GBG production (more gas per kg fuel fed) and lowering the tar content [3]. Catalyst cracking of tar in a separate unit downstream the gasifier is another application of catalyst material that have been claimed to completely destroy the tar [4]. However, except from their conversion efficiencies, the catalyst materials themselves suffer from high price and de-activation due to sulphur poisoning which then shortening their lifetime. In another method, thermal treatment of the tar at high temperature may save the energy efficiency by eliminating the GBG cooling and reheating process. But, a thermal cracking method requires supply of energy for the high temperature requirement and high temperature reactor material.

From the studies mentioned above, it can be concluded that the current progress of tar removal technologies are either complicating the overall gasification process or increasing the operation cost. From the positive side, the presence of non-condensed tars in the GBG in the gasifier outlet contributes to an improved heating value of the gas. Therefore, employment of the 'dirty' hot GBG directly from the gasifier in combustion devices has a significant benefit in the combustion process [5–8].

Laminar flame speed is one of the essential parameters to characterize the combustion behaviour of GBG as it contains information on reactivity, diffusivity and exothermicity. On a practical level, the laminar flame speed is used to predict flashback, blow off, and flame stability. In a more fundamental level, it is an important target to validate chemical kinetics of the reacting mixture and is used in numerical study of combustion.

There are abundantly available measured and calculated laminar flame speed data for a single fuel such as CH_4 [9,10] and H_2 [9] at a variety of operating conditions. These studies show that the flame speed strongly is influenced by the air–fuel-ratio, pressure, and preheating temperature. A great amount of studies of laminar flame speed are also available for binary fuel mixtures such as CH_4/H_2 [11], CH_4/CO [12] and CO/H_2 [13,14]. However, fewer studies discovered the laminar flame speed of gas mixtures mainly consisting of the major combustible components of the GBG, which by definition is a mixture of $CO/H_2/CH_4/CO_2/N_2$ [15].

Liu et al. [16] considered various gaseous fuels, i.e. the GBG from Värnamo plant, pyrolysis gases, landfill gases and syngas (CO/H_2 mixture) in a (kinetic) model of laminar flame speed at normal temperature and pressure. They determined the reaction zone structure and flame thickness, purposely to provide correlation between flame speed and the gas composition. The result showed that the laminar flame speed linearly increases with increased mole fraction of H_2 in the gasification gas, syngas or pyrolysis gas. Monteiro et al. [15] measured the laminar flame speed of $H_2/CO/CH_4/CO_2/N_2$ fuel mixtures which simulated the GBG of updraft, downdraft respective fluidized bed gasifier at normal temperature and pressure, over a range of equivalence ratios employing a spherically expanding

flame and Schlieren photography. They found that the maximum laminar flame speed is observed at stoichiometric conditions with the fuel mixture of downdraft gasifier showing the highest value, followed by updraft and fluidized bed. Ouimette and Seers [17] numerically determined the laminar flame speed of $H_2/O_2/N_2/CH_4/CO/CO_2/C_2H_4/C_2H_6$ mixtures, which reassemble the wood residue GBG of pilot plant gasification process in the city of Sherbrooke in Canada. The calculations are performed using PREMIX, a module in CHEMKIN over different equivalence ratios, initial reactant temperatures and pressures. The numerical simulation showed a good agreement with their experimental data of flame speed measurement using rim-stabilized conical flame. They claimed that the slower laminar flame speeds of wood syngas compared to methane is caused by its lower low heating value.

The present study is motivated by the lack of data on laminar flame speeds of gasified biomass gas with its main mixture compositions where H_2O and/or tars are included. Therefore, more attention must be given to the variation in the GBG mixture compositions and their effects on the laminar flame speed. H_2O is an important constituent in product of gasification process and its presence in the fuel mixture can give significant dilution impact. The influence of H_2O addition on laminar flame speed measurement of H_2/CO –air mixture was reported by Das et al. [18]. They found that for small H_2/CO ratio, the laminar flame speed is increased for lower percentage of H_2O but is decreased as the percentage of H_2O is increased beyond a critical value. However, for higher H_2/CO ratio, the laminar flame speed is decreased with increased H_2O addition. No data was found for laminar flame speed of $CO/H_2/CH_4/CO_2/N_2$ with H_2O addition. Duan et al. [5] reported that addition of toluene (C_7H_8) as a tar compound in $CO/CH_4/H_2/CO_2$ mixture has a positive impact on NO-reduction when the fuel mixture including tar is injected into a coal-fired boiler as a reburning fuel. The fuel mixture with a tar component showed stronger effect of temperature on NO reduction compared to fuel mixture without presence of the tar compound. Liu et al. [6] reported that different tar model compounds i.e. benzene (C_6H_6), toluene (C_7H_8), styrene (C_8H_8) and phenol (C_6H_5OH) have different effect on NO reduction. Phenol showed the highest NO reduction efficiency, while for C_6H_6 the NO reduction efficiency is correspondingly low under the same temperature ranges. For toluene and styrene, the NO reduction efficiency is increased with temperature. No study was found examining the influence of tar compounds on laminar flame speed of GBG mixture.

Therefore, the objective of the present study is to investigate influence of H_2O vapour and tars on laminar flame speeds of the GBG. In addition, the thermodynamic and transport properties of the fuel mixture are studied here. The GBG fuel mixture used is simulated the GBG produced by atmospheric downdraft gasifier of wood pellet as published by Erlich and Fransson [19]. Since it is very difficult to identify its different compounds present in real

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