DESIGN PRINCIPLES AND FABRICATION METHOD FOR A MINIATURIZED FUEL GAS COMBUSTION REACTOR

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ABSTRACT

Wobbe Index meter is widely used to reflect the energy content and gas quality of a fuel gas mixture. It is highly in demand to downscale from the conventionally large Wobbe Index facility to a miniaturized Wobbe Index meter. Therefore spontaneously combustion of the fuel gas/air mixtures on a MEMS-based combustor can provide in-line temperature monitoring of the combustion produced heat. However, flame can be quenched by the channel walls when the walls are closely spaced. Therefore, it is crucial to design a micro-combustor with good thermal management and strong mechanical stability. MEMS-based Trench-Assisted Surface Channel Technology is designed and developed to realize these large-volume suspended combustor structures.

KEYWORDS

Micro-Combustion; Exothermic Microreactor; Micro-flame Quenching; Trench-Assisted Surface Channel Technology.

INTRODUCTION

Gas exchangeability

The composition of natural gas originating from different countries differs substantially. In the Netherlands, real-time information of the natural gas composition is getting more important since the Dutch gas grid will change with the introduction of biogas, hydrogen and foreign natural gas.What's more, the transition of natural gas payment from per cubic meter to per amount of heat generated also requires precise in-line gas quality monitoring. Gas blends need to be tuned to deliver a constant energy content to the end-users. Wobbe Index is widely used in many countries to reflect the energy content of fuel gases.[1] For any given orifice, all the gas mixtures that have the same Wobbe Index will deliver the same amount of heat and are interchangeable.[2]

Wobbe Index

Wobbe Index is calculated by the Higher Heating Value and the square root of the Specific Gravity of the fuel gas, as shown in equation (1).

$$\text{Wobbe Index} = \frac{\text{Higher Heating Value}}{\sqrt{\text{Specific Gravity}}} \tag{1}$$

Heating values [$\mathrm{MJ\,kg^{-1}}$] of a fuel are used to quantify the maximum amount of heat that can be generated by the fuel combustion with air at the standard conditions (25 °C and 101.3 kPa). The amount of heat release from the fuel combustion will depend on the phase of water in the products. If the product water is in the gas phase, the total heat release value is denoted as the Lower Heating Value (LHV). When the water vapor is condensed to liquid, additional energy equals to the latent heat of water vaporization can be extracted. The value of the total energy release is called the Higher Heating Value (HHV). The value of the LHV and HHV is related by the amount of energy released during the phase change of water between the vapor and liquid, as shown in equation (2):[3]

$$\text{LHV} = \text{HHV} - \frac{N_{\mathrm{H_2O,\,P}} \times M_{\mathrm{H_2O}} \times h_{fg}}{N_{\mathrm{fuel}} \times M_{\mathrm{fuel}}} \tag{2}$$

where $N_{\mathrm{H_2O,\,P}}$ is the number of moles of water in the products and $M_{\mathrm{H_2O,\,P}}$ is the molecular weight of water. Latent heat for water at standard conditions is $h_{fg} = 2.44\ \mathrm{MJ\,kg^{-1}}$. N_{fuel} is the number of moles of fuel burned and M_{fuel} is the molecular mass of the fuel.

Specific Gravity, also called relative density, is defined as the density of the fuel gas divided by the density of dry air of standard composition at the same specified conditions of pressure and temperature.[3]

Higher Heating Value from a constant-volume reactor

For a closed system of the constant-volume reactor, at the standard conditions, the Higher Heating Value of a fuel is calculated as shown in equation (3):[3]

$$\mathrm{HHV} = \frac{-Q^0_{rxn,v} - (\sum_i N_{i,\mathrm{P}} - \sum_i N_{i,\mathrm{R}}) \times \hat{\mathrm{R}}_u \times \mathrm{T}_0}{N_{\mathrm{fuel}} \times M_{\mathrm{fuel}}} \tag{3}$$

where $N_{i,\mathrm{P}}$ and $N_{i,\mathrm{R}}$ are the number of moles of spieces i in the product and reactant, respectively. $\hat{\mathrm{R}}_u$ is the universal gas constant and T_0 is the standard temperature. N_{fuel} is the number of moles of fuel burned and M_{fuel} is the molecular mass of the fuel. The amount of heat transfer $-Q^0_{rxn,v}$ flows from the combustion system to the environment can be estimated depends on the specific heat exchange mechanism of the reactor, namely convective heat transfer, conductive heat transfer and radiative heat transfer.

DESIGN PRINCIPLES FOR A SMALL-SCALE WOBBE INDEX METER

Miniaturization of Wobbe Index meter

For the central heating systems and fuel gas supplies industries, conventionally available Wobbe Index facilities have large volume of around $1\,\mathrm{m}^3$. Moreover, they cost more than $50,000$€ and consumes large quantities of gas sample to measure the Wobbe Index of the fuel gas. For in-line gas quality monitoring and easy operations in the remote areas, an on-chip Wobbe Index meter[4] shows promising benefits of downscaling both the device size and the energy consumption when comparing to the currently available systems.

Our envisioned integrated Wobbe Index meter consists of a gas density sensor and a small-scaled combustor fabricated by the same MEMS technology. Proof-of-concept for a density sensor has been demonstrated from the micro-Coriolis flow sensor.[5] Here we will discuss the design principles and propose a fabrication technology to realize the small combustor. Future work is planned to design and fabricate a gas density sensor by the same technology.

Our approach to experimentally obtain the HHV value of the fuel gases is by performing complete combustion of the fuel gases on-chip with precise temperature monitoring and in a controlled volume combustion chamber. The combustor chip design consists of mainly three functional parts, namely the mixer, preheater and combustor. Stoichiometric fuel gas and air are first sufficiently mixed in a diffusion-driven mixing channel. Then the well-mixed combustible gas mixture can be preheated to just below the auto-ignition temperature of the fuel gas. Once the complete combustion takes place in the designated combustion chamber, the flame temperature and flame burning velocity can be measured and deduced by the local temperature sensor. Finally, HHV of fuel gases can be further calculated by thermodynamic relations depends on the mechanism of the heat transfer from the hot combustor to the temperature sensor.

However, down-scaling of the combustor sizes introduces new problems, namely the micro-flame quenching phenomena.

Flame propagation

Fuel gas complete combustion with the stoichiometric or excess air is a highly exothermic reaction. The reaction has a self-propagating reaction zone which is also known as flames. The burning velocity and the flame temperature are the two characteristic properties of flames. Flames will propagate through the stationary unburnt gas mixture at a characteristic burning velocity. The velocity of this wave is controlled by both the diffusion of heat and the diffusion of active radicals. In details, a larminar flame propagation in premixed gases has two mechanisms: firstly, the unburnt mixture is conductively heated by the burnt zone and become sufficiently rapid to start self-propagating. Secondly, the active radicals diffuse from the burnt reaction zone to the unburnt mixture and ignite the exothermic reaction. Therefore, both mass and heat diffusion of the active radicals contribute to the propagation of the reaction zone and determines the burning velocity and flame temperature. However, down-scaling of the combustor channel dimensions from macro-sizes to micro-sizes will probably cause flame quenched by the closely-spaced walls.

Down-scaling caused flame quenching

Fuel gas combustion in small-scale channels has been reported to suffer from flame extinction.[6] In the microchannels where the surface-to-volume ratio is so large that the heat loss through the channel wall surfaces to the environment becomes substrantial. Once the heat loss to the surroundings is even larger than the heat generated from the exothermic combustion reaction, the flame or the reaction zone stops propagating in the channel and extinguishes,this is known as the thermal quenching of the micro-flames.[6] Therefore, in order to maintain continuous flame propagation, there exists a threshold where the characteristic channel dimension must be larger than the critical quenching diameter of the fuel gas.[7] Good thermal management of the combustion reactor is crucial to surpress the thermal quenching of the micro-flames. Promising results from the Swiss-Roll combustors[8] have shown that the excess enthalpy or heat recirculation can extend the flame flammability limit to even under the traditionally known critical quenching distance for the fuel gas.

Another down-scaling effect taking place in the small combustion reactors is the radical quenching. When the characteristic channel diameter is not much larger than the mean free path of the reactants molecules, a substantial amount of active radicals would easily diffuse from the homogeneius combustion zone to the surface of the inner walls. These heterogeneous radicals adsorption and recombination at the inner wall surface would cause the flame quenched even when there is little heat loss to the environment.[7] A straightforward solution to minimize the radical quenching is to choose chemically inert channel inner wall materials. Also, temperature of the channel walls plays a major role to control the kinetics of the adsorption, recombination and desorption of the radicals and molecules.

Summary of the combustor design principles

In order to fabricate a small-sized combustor to burn the fuel gas on chip and measure the elavated temperature from the combustion produced heat, it is necessary to maintain a continuous flame propagation without flames extinction induced by thermal quenching or radical quenching. The most important principles for designing a micro-combustor are as follows: Firstly, design a combustion channel with sufficiently large cross-sectional area is the key principle for sustaining a continuous flame propagation. In addition, excess enthalpy can be supplied to the system by heating up the combustor channel walls and preheat the unburnt gas mixtures. Moreover, chemically inert wall material and channel wall temperature tuning is key to reduce radical quenched by the wall. Finally, a reliable and accurate local temperature sensor is essential for in-line monitoring the flame location and burning speed.

TRENCH-ASSISTED SURFACE CHANNEL TECHNOLOGY

We developed a micromachining fabrication process called Trench-Assisted Surface Channel Technology (TASCT) to realize such a micro-combustor with a large internal volume. TASCT is evolved from the concept of the Surface Channel Technology[9][10] developed for the micro-Coriolis chips, where the silicon wafer is isotropically etched through the small-slit pattern to create channels right underneath the surface of the wafer.

These surface channels have the cross-sectional shape of a partially circular channel with a flat top, the channel size and shape are determined by the designed slits pattern. Channels with diameter around 300 μm can still be made by the Surface Channel Technology. However, the mechanical stability are likely to decrease once the channel diameter becomes larger. In order to make channels with larger cross-sectional area, we introduce new features of high aspect-ratio trenches into the Surface Channel Technology concept.

The TASCT process requires a SOI wafer and all the channels are realized in the device layer. The fabricated channels and chambers have a rectangular cross-section, as illustrated in Figure 1 of a SOI wafer with cross-sectional view. The height of the channel side walls is 50 μm, which is defined by the device layer thickness of the SOI wafer. Surface channels of any desired planar shape and dimension can be achieved through the combination of the high aspect-ratio refilled trenches and the Surface Channel technology. SOI wafer is heavily doped and the silicon heaters are defined by the 3 μm wide trenches to heat up the chamber side walls. Platinum heaters and temperature sensors are placed on top of chamber to heat up the chamber roof membrane and sense the temperature variation. To provide thermal isolation, large cavities can be made underneath and to the sides of the combustion chamber. Flexure structures are made of channels across the side cavities and they are not depicted here.

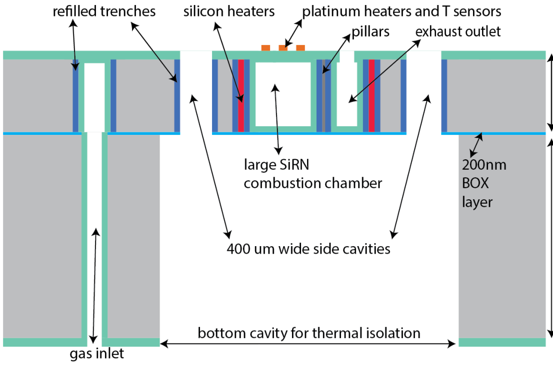

Figure 1: Schematical cross-sectional view of a suspended large-volume combustion chamber using TASCT fabrication process, key features are indicated in the illustration.

A more detailed description of TASCT can be found in the MFHS extended abstract submission from H.-W. Veltkamp with the title ”Fabrication of Large-Volume Rectangular Channels using Trench-Sidewall Technology and A SOI Substrate”.

CONCLUSION AND FUTURE WORK

In conclusion, we discussed the motivation of developing a miniaturized Wobbe Index meter. Flame quenching phenomena in the small channels drive us to discover the principles when designing the micro-combustor suitable to have continuous combustion of the fuel gas. We also developed an innovative fabrication method TASCT to realize a large-volume combustor channel with good thermal management and strong mechanical strength from a SOI wafer. Future work will be continuing the fabrication of a complete Wobbe Index meter with the integration of all the fluidic connections and heat management electronics to perform fuel gas combustion on the chip.

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REFERENCES

[1] Union, I. G. (2011). Petroleum B. guidebook to gas interchangeability and gas quality.

[2] Zachariah-Wolff, J. L., Egyedi, T. M., and Hemmes, K. (2007). From natural gas to hydrogen via the Wobbe index: The role of standardized gateways in sustainable infrastructure transitions. International journal of hydrogen energy, 32(9), 1235-1245.

[3] McAllister, S., Chen, J. Y., and Fernandez-Pello, A. C. (2011). Fundamentals of combustion processes. New York: Springer.

[4] Lötters, J. C., Lammerink, T. S., Pap, M. G., Sanders, R. G., de Boer, M. J., Mouris, A. J., and Wiegerink, R. J. (2013, January). Integrated micro Wobbe index meter towards on-chip energy content measurement. In Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on (pp. 965-968). IEEE.

[5] van der Wouden, E., Groenesteijn, J., Wiegerink, R., and Lötters, J. (2015). Multi parameter flow meter for on-line measurement of gas mixture composition. Micromachines, 6(4), 452-461.

[6] Ju, Y., and Xu, B. (2005). Theoretical and experimental studies on mesoscale flame propagation and extinction. Proceedings of the Combustion Institute, 30(2), 2445-2453.

[7] Maruta, K. (2011). Micro and mesoscale combustion. Proceedings of the Combustion Institute, 33(1), 125-150.

[8] Ju, Y., and Choi, C. W. (2003). An analysis of sub-limit flame dynamics using opposite propagating flames in mesoscale channels. Combustion and Flame, 133(4), 483-493.

[9] Groenesteijn, J., de Boer, M. J., Lötters, J. C., and Wiegerink, R. J. (2017). A versatile technology platform for microfluidic handling systems, part I: fabrication and functionalization. Microfluidics and Nanofluidics, 21(7), 127.

[10] Dijkstra, M., De Boer, M. J., Berenschot, J. W., Lammerink, T. S. J., Wiegerink, R. J., and Elwenspoek, M. (2007). A versatile surface channel concept for microfluidic applications. Journal of Micromechanics and Microengineering, 17(10), 1971.

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