# Experimental study of the heat recovery rate in a porous medium combustor under different hydrogen combustion modes

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## ABSTRACT

This study investigated the heat recovery rates of hydrogen flame modes in porous medium combustion. The porous medium was oxide-bonded silicon carbide (OB-SiC), aluminum oxide ($Al_2O_3$) or zirconia ($ZrO_2$) with 60 or 30 PPI. The results indicated that the reaction temperature of a flame mode was controlled by the equivalence ratio (flame velocity), thermal load and solid medium thermal properties ($k$ and $C_P$). The operation region of the flame modes was controlled by the equivalence ratio and dimensionless velocity ($V^*$). Under ultra-lean conditions ($\Phi = 0.2-0.25$), the flame was blown out when the dimensionless velocity was above 4.5 for OB-SiC and $Al_2O_3$ settings. In contrast no blow out occurred for the $ZrO_2$ setting and under a high equivalence ratio ($\Phi > 0.4$), and the flame mode was a conical flame when the dimensionless velocity was above unity. The heat recovery mechanism of surface and interior combustion was based on the conduction and radiation of the porous medium. The dimensionless temperature ($\theta^*$) is defined as the ratio of the reaction temperature over the adiabatic flame temperature. When the dimensionless temperature was unity, the reaction temperature approached the adiabatic flame temperature. Under interior combustion, the maximum dimensionless temperature was 0.994 for the OB-SiC ($\Phi = 0.3$) setting. Furthermore, the maximum dimensionless temperature was 0.942 for $Al_2O_3$ and 0.969 for $ZrO_2$ under operation at $\Phi = 0.3$. The heat recovery rate of hydrogen combustion under surface and interior combustion was thus higher than that of the conical flame mode.

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## Introduction and literature review

Gas fuel is widely used for industrial and commodity heating applications, *e.g.* metal welding, heat treatment for steelmaking and home heating. In the design of combustors (burners), the equivalence ratio and flame velocity are two very important parameters for premixed combustion. In practical applications, a combustor would operate under fuel lean conditions in order to prevent flashback and nitrogen

oxide formation (thermal $NO_x$), although the problem of flame instability could arise in this context [1]. In the reaction zone, the flame would be affected by flow disturbances due to heating and expansion of combustion. The disturbance of the expanded gas causes hydrodynamic instability, and the non-homogeneous thermal diffusion would cause diffusive-thermal instability. These instabilities will be more obvious in micro-scale combustion systems [2–4]. According to a review study [2], in microsystems the surface to volume ratio (aspect ratio) is larger than that in normal systems, and thus the heat loss will be larger than the heat released from fuel. The reaction heat can be transferred to the environment by conduction, convection or radiation. If the heat loss rate is too high, abnormal combustion phenomena will occur due to a low temperature, *e.g.* cellular flame, flame flicking or extinction.

Hydrogen has a low ignition energy (0.02 mJ) [5,6], and thus combustion with the addition of hydrogen could extend hydrocarbon fuel flame stability, flammability and prevent misfiring [7]. Hydrogen is the simplest chemical element, and also the most abundant in the universe. The advantages of hydrogen include a widest flammability limit (Vol. % = 4–75%), high adiabatic flame temperature and fast laminar flame velocity ($S_L$ = 290 cm/s, $\Phi$ = 1.0). As a fuel, hydrogen can be easily reacted even under dilute content [8,9]. Kito et al. [8] studied a hydrogen flame jet igniter for methane/air combustion. Their combustion chamber was filled with methane and air, with the equivalence ratio ranging from 0.3 to 1.0. The hydrogen flame jet igniter produced high temperature gas and radicals via hydrogen combustion. Methane/air premixed gas was ignited by hot gas and radicals of the igniter under lean equivalence ratio conditions. The results showed that methane/air could be ignited under $\Phi$ = 0.34, which is lower than the figure seen for the lean flammability of methane ($\Phi$ = 0.5).

Lecoustre et al. [9] studied the hydrogen flame hazards associated with small leaks in microsystems. Due to its high flammability, a hydrogen flame can be stable under a low feeding rate. In their experiment, the hydrogen feeding rate was set at 3.9 and 2.1 μg/s, and was mixed with air or oxygen. A weak and stable flame could be observed at low heat release rate of 0.46 W for $H_2$/air and 0.25 W for $H_2/O_2$.

A combustion flame transfers thermal energy to the surroundings by conduction, convection or radiation. In a combustion system, conduction happens at the interface of burning gas and un-burned gas; convection happens between the high temperature gas and wall; while radiation transfers heat to the surroundings by flame light. In a combustor, gas is heated on a flame sheet and gas molecules turn to an excited state and then change to the groundstate and immediately release light and heat. The magnitude of emissive power depends on the species concentration of the combustion product and optical thickness of the flame [10,11]. The main products from hydrocarbon fuel combustion are water vapor and carbon dioxide. The wave-lengths emitted from such combustion are around 700 nm ($H_2O$) and 300–500 nm ($CO_2$). Soot particles are also the main products in a hydrocarbon diffusion flame, and the wave-length is 400–500 nm ($C^*$), with the color being yellow or orange. These three products are important light emission sources in the study of hydrocarbon flames.

However, the main products of hydrogen flames are water vapor and hydroxyl radicals ($OH^*$, $\lambda_{OH^*}$ = 295–325 nm). Since the spectrum of hydroxyl radicals is ultraviolet light, the hydrogen flame cannot be observed by the human eyes, except for the red light of water vapor ($\lambda_{H_2O}$ = 600–900 nm). Schfer et al. [12] studied the flame colors of hydrogen premixed and diffusion flame. They found that these depend on the purity of the gas supply. In the combustion process, the micro-content of carbon dioxide in the atmosphere produces $CH^*$ on the flame sheet, and thus blue emissions are observed due to $CH^*$ radicals ($\lambda_{CH^*}$ = 430 nm) in the $H_2$/air flame. Under stoichiometric conditions a reddish color is observed on the flame tip due to water vapor. However, when the water vapor concentration decreases, the reddish light becomes invisible under leaner conditions. A hydrogen flame is thus not easy to observe, since the flame color is lighter than those of methane and propane. Huang et al. [13] studied the effects of the addition of carbon dioxide and carbon monoxide on the hydrogen flame. The results showed that the intensity of the 400–500 nm wave length was raised in the spectrum. In addition, the light emitting intensities of hydroxyl and water vapor were decreased, and the blue light emitted from $CH^*$ increased due to the addition of $CO_2$ and CO.

As seen in the references outlined above, most gaseous fuel ($CH_4$, $H_2$) combustion produces carbon dioxide and water vapor ($CO_2$ and $H_2O$), and generates nonluminous radiation [14], while the product of hydrogen combustion is water vapor. However, the emissive power of the enthalpy of gas is low due to thin optical thickness, and thus the heat recovery rate decreases in the combustion system due to weak emission power, as shown in Fig. 1 [15]. Increasing the optical thickness by using materials with greater emissive power (*e.g.* a porous plate) would produce a greater amount of converted radiation energy, and this would propagate to upstream of the gas flow direction. As such, the reaction temperature would be raised via increasing heat recovery.

Some studies have tried to recover the waste heat from exhaust gas and raised the upstream gas temperature in order to enhance the heat recovery rate of gaseous fuel combustion [3,4], such as with the use of a Swiss roll burner and exhaust
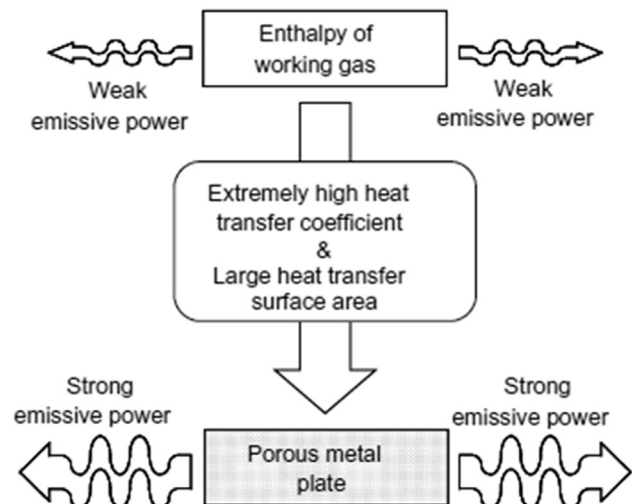


Fig. 1 – **Effective energy conversion mechanism [15].**