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The effect of copper flame holder application on butane combustion characteristics in meso-scale combustor

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Abstract. This experimental research aims at determining the characteristics of butane combustion in Mesocombustor made of a quartz glass tube with a diameter of 3.5 mm and an outer diameter of 5 mm. The findings revealed that the flammability limit became wider with sharp curve narrowing. The narrowing of flammability limit did not occur in the other flame holder made of mesh stainless steel. Different from stainless steel conductivity, copper has declining thermal conductivity in each of temperature increase. The wider flame section was due to the increase of temperature in each flow velocity.

Keywords: mesocombustor; flame holder; thermal conductivity rate; flammability limit; visualization; temperature.

1. Introduction

Micropower generator with hydrocarbon fuel might become a potential alternative due to its greater fuel density than those contained in batteries [1][2]. One type of Micropower generator has two important parts, which are thermophotovoltaic (TPV) and micro or meso scale combustor. Thermophotovoltaic (TPV) is a material that is able to convert heat into ready-to-use electricity. Micro or meso scale combustor functions as a converter from chemical fuel into heat [3]. To simplify this discussion, micro/meso-scale combustor, hereinafter, is called mesocombustor.

Maintaining the flame stability in mesocombustor is difficult due to the short residence time of mesocombustor and high heat loss [4]. The main important issue to create flame stability in mesocombustor is to minimize thermal quenching due to heat loss [5].

An experiment of flame stabilizing in mesocombustor tube with stainless steel flame holder application had been conducted by Yuliati, et al. [6]. The experiment revealed the effect of thermal conductivity of mesocombustor partition on flame stability in mesocombustor. A similar experiment to stabilize the flame of liquid fuel was conducted by using quartz mesocombustor with an addition of steaming segment insertion of stainless steel flame holder [7]. The flame holder is a part of mesocombustor in which the flame is located nearby. Flame holder functions as heat recirculatory assistor from the heat into reactant. Heat recirculatory aims for the reactant's initial heating before entering the combusting zone, by minimizing the heat loss. [6-8].

One of the materials with the highest thermal conductivity is copper. This article seeks to examine the effect of copper flame holder application on butane combustion characteristics in quartz tube mesocombustor.

2. Method

The mesocombustor design can be seen in Figure 1 while the experiment installation is illustrated in image 2.2. The mesocombustor was made of quartz glass tube with an outer diameter of 5 mm and inner diameter of 3.5 mm. A copper flame holder with a thickness of 1 mm was placed between them. The flame holder material was copper with thermal conductivity in the room temperature of 386 W/m.K [9] and stainless steel with the thermal conductivity of 16.3 W/m.K [9]. The temperature was measured on the 2 mm partition of inlet (T1), the 2 mm of outlet (T2), the flame (T3), and the combustion gas in the outer layer of flame holder (T4). The scheme of experimental installation which is containing parts of 1. Compressor; 2. Butane Gas; 3. Air Flowmeter; 4. Gas Flowmeter; 5. Mesocombustor; 6. Camera; 7. Thermocouple; and 8. Mesocombustor holder are shown in Figure 2.

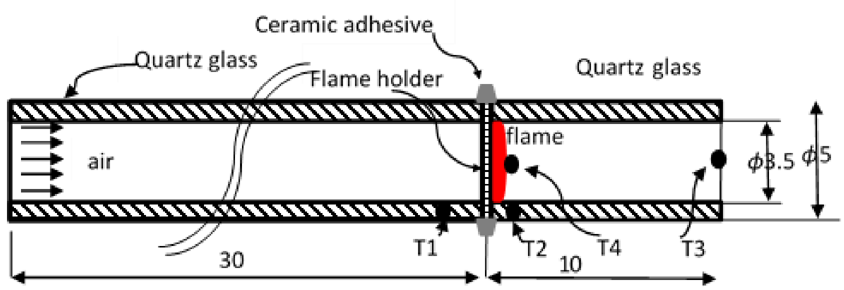

Figure 1. Mesocombustor and temperature measurement spot

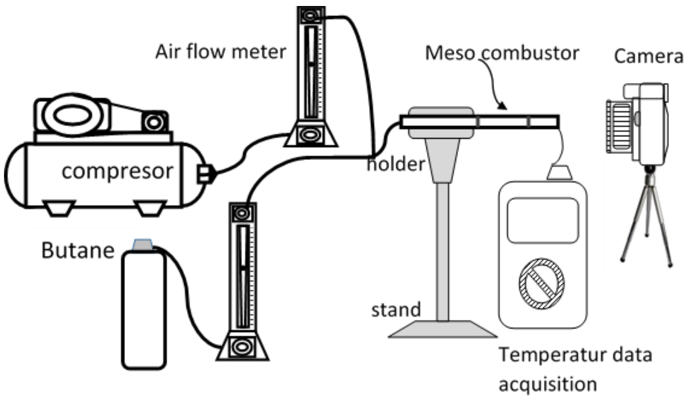

Figure 2. Experiment Installation Scheme

The flame visualization was captured by Nikon D5200 Camera. The fuel used in this experiment was butane gas (C_4H_{10}). The flowmeter was used to measure the flow velocity of air and gas into mesocombustor. The flow velocity of air and gas was made varied from the lowest to highest value, with a stable flame inside the mesocombustor.

The examined combustion characteristics involved flammability limit, flame visualization, and temperature. Meanwhile, the flame visualization was captured by a macro lens camera, and the temperature was measured by using thermocouple.

3. Result and Discussion

In Figure 3, a stable flame occurred in the equivalence ratio ϕ between 0.7 and 2.15, most of them occurred in equivalence ratio of ϕ>1, or rich mixture zone. The copper's flammability limit was wider than the one made of stainless steel due to the higher thermal conductivity value (386 W/m.K for copper and 16.3 W/m.K for stainless steel). Higher thermal conductivity causes more heat energy distributed to the outlet, in order to heat the reactant. Copper has wider flammability limit than stainless steel, yet it has a deviation in the form of sharp narrowing and irregularity of flow velocity above 55 cm/s.

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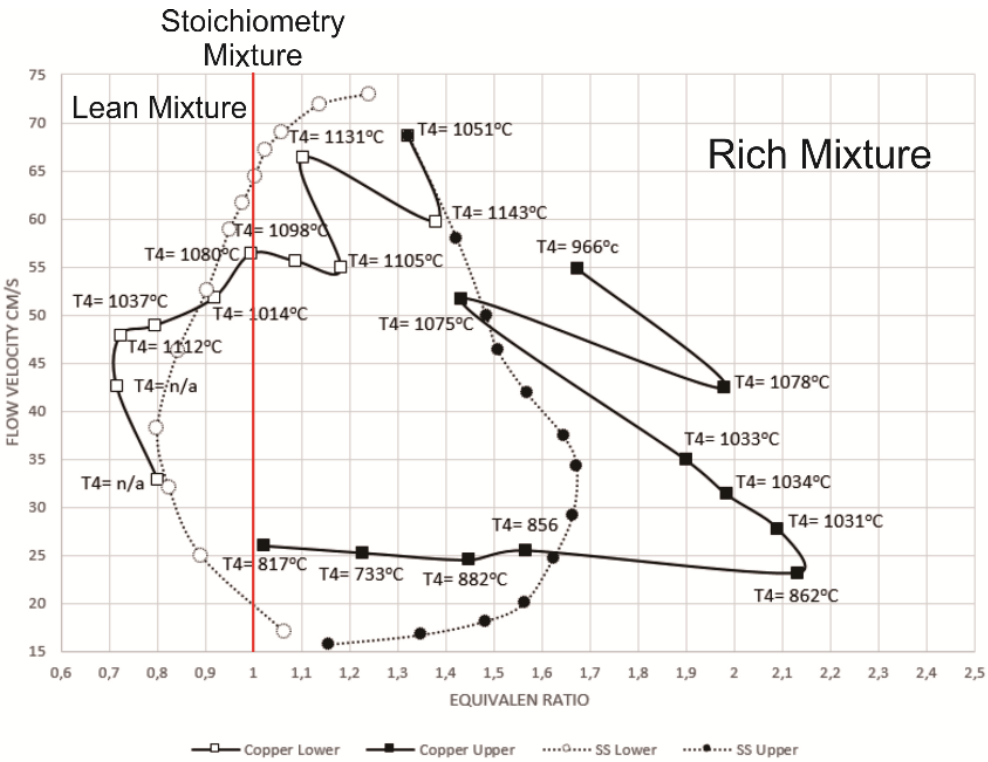


Figure 3. Relationship between equivalence ratio and mixture flow velocity

In Figure 3, the deviation of lower limit starts at φ1.18; U 54.8; T4 (flame temperature) 1033°C, and the upper limit starts at φ 1.4; U 51; T4 1131°C. Copper's thermal conductivity would decrease when the temperature increased.

The decrease of copper's thermal conductivity was due to the lattice structure's irregularity. The rising temperature would damage the lattice structure and decrease the conductivity rate due to the distributed electron movement through the lattice [10]. This decrease affected the amount of heat distributed to the inlet of mesocombustor. A higher reactant's flow velocity caused higher heat produced and higher heat needed to warm up the reactant. If the flame holder's conductivity decreases, the heated velocity to be recirculated to the inlet will also decrease. The decrease of heat velocity would affect the flame stability in mesocombustor and made the flammability limit narrow suddenly.

The stainless steel used in this research was grade 304 which had opposite characteristics with copper. Copper's thermal conductivity would decrease when the temperature increased while stainless steel's thermal conductivity would increase when the temperature increased. Based on the international standard table, the thermal conductivity of stainless steel grade 304 in the temperature of 100^0C was 16.3 W/m.K and temperature of 500^0C was 21.5 W/m.K. The increase of thermal conductivity caused a more regular flammability limit because higher temperature causes more heat needed to warm up the reactant. Thereby, by the increase of thermal conductivity, the needed heat energy to warm up the reactant as well as the flame stability could react well. This was proven by the stainless steel's flammability limit that reached the highest point in the mixture's flow velocity. The illustration can be seen in Figure 3.

Stainless steel has a lower thermal conductivity than copper; so, it has a narrower flammability limit than copper. On the other hand, copper has a higher conductivity yet there is a sudden narrowing in its flammability curve. The copper application for the flame holder in mesocombustor needs to be reconsidered because its thermal conductivity would decrease when the temperature increased. The flame and temperature visualizations are illustrated in Figure 4.

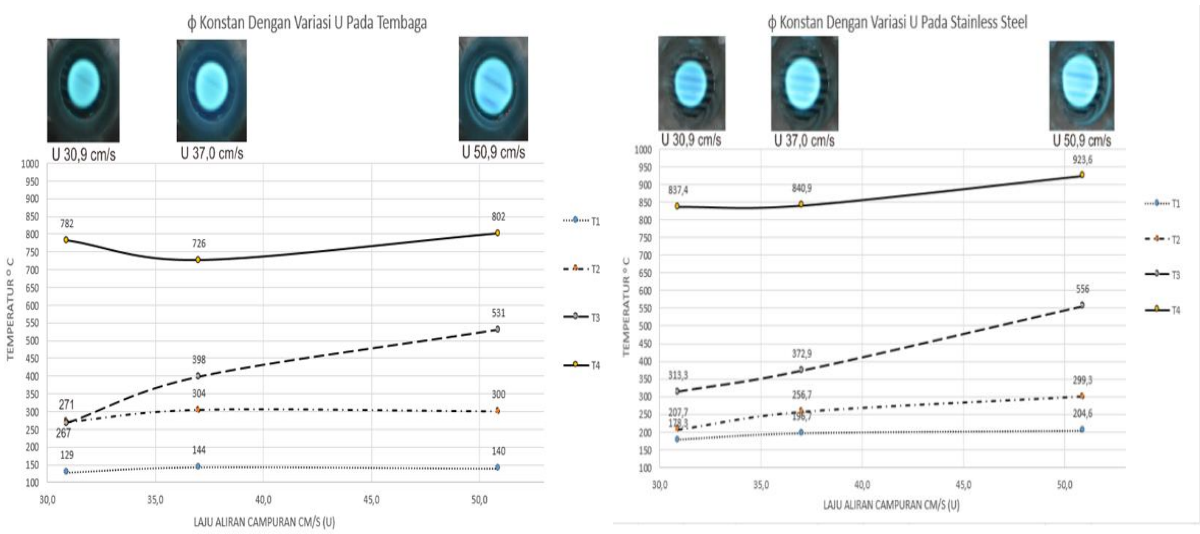


Figure 4. Flame visualization in φ 1,3 with varied mixture flow velocity (U)

Figure 4 illustrates the relationships between flow velocity, temperature, and flame visualization. The visualization above was taken in U 30,9 cm/s; 37 cm/s dan 50,9 cm/s and equivalence ratio (φ) was made constant at 1.3. The image above showed that the flammability limit got wider and the temperature increased as the mixture flow velocity increased.

In the flow velocity of lean mixture (U = 30,9 cm/s), the reactant supply for low mixture combustion was low, so the combustion would generate lower heat. The low heat was not sufficient to provide activation on reactant and produced gap without combusting reaction or quenching distance. The reactant in quenching distance cooled the combustion space, and the heat loss into environment causes the quenching distance got thicker. On the other hand, the flow velocity of high mixture (U = 50.9 cm/s) generated a higher heat level. The high heat level was able to transfer sufficient activation energy to reactant, which causes the quenching distance narrow. The increase in temperature was proportionate as the increase in flow velocity. The illustration was given in Figure 4.

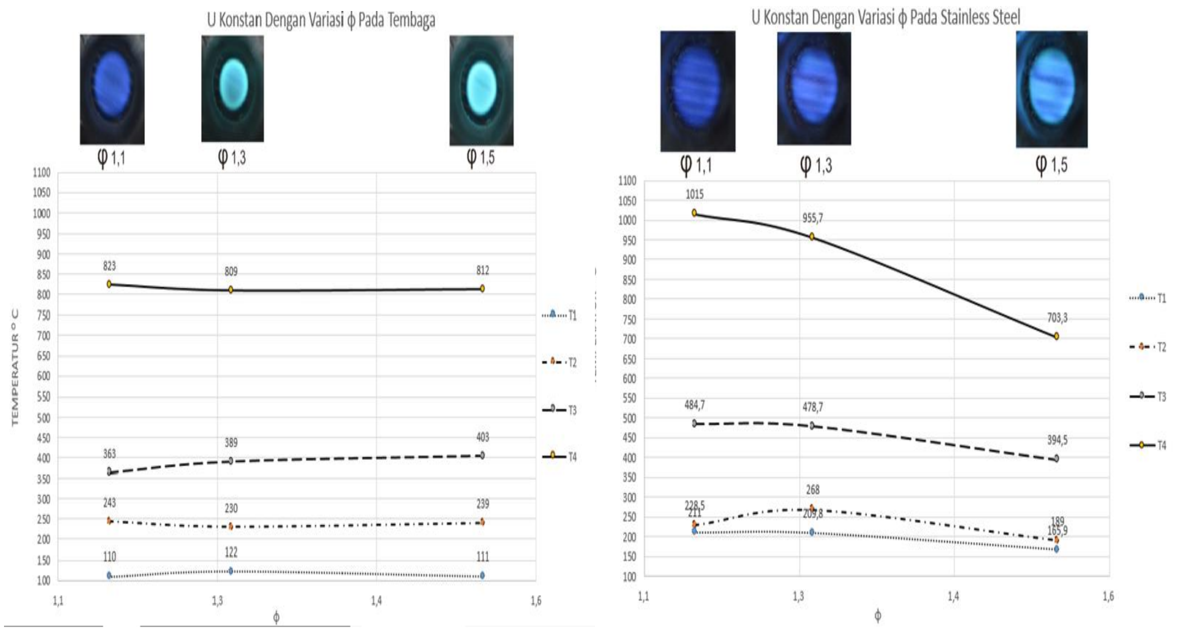
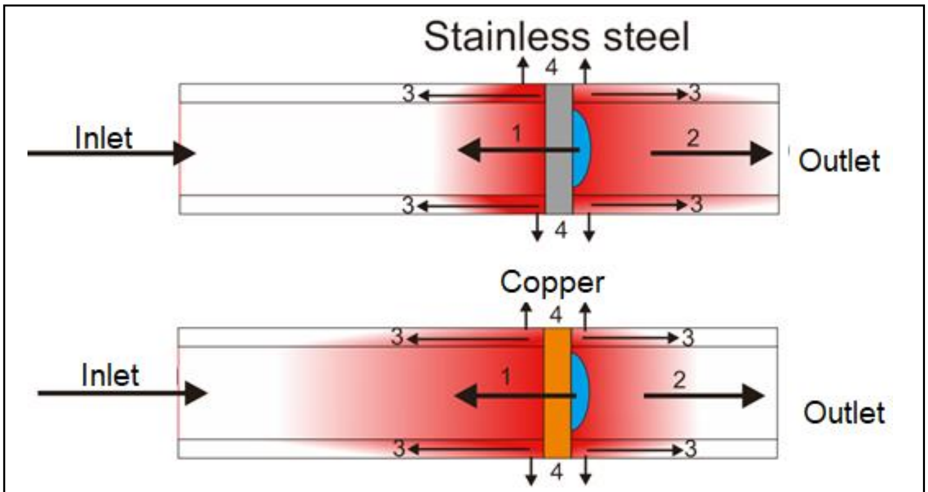


Figure 5. Flame visualization in U 38 cm/s with varied equivalence ratio (φ)

In Figure 5, it shows that in the equivalence ratio of 1.1, both stainless steel and copper produced dark blue flame. Meanwhile, in the equivalence ratio of 1.3 and 1.5, the color became bright blue. In lean mixture (equivalence ratio of 1.1), the flame became darker due to the lack of fuel in the mixture. Otherwise, in rich mixture (equivalence ratio of 1.3), the flame became brighter, and in the richest mixture (equivalence ratio of 1.5), the flame became much brighter. It can be concluded that rich mixture produced a brighter flame while lean mixture produced a darker flame color.



Note : 1: Heat convection into the inlet of mesocombustor (heat needed to warm up the reactant); 2: Heat convection to the outlet (heat emission with the gas); 3: Heat conduction through glass partition; 4: Heat conduction from the mesocombustor's partition to the environment.

Figure 6. Illustration of heat distribution in mesocombustor's inlet and outlet due to thermal conductivity difference

In Figure 6, it shows that stainless steel, which has a lower thermal conductivity than copper, when the combustion occurred, the generated heat was not quickly conducted into the inlet (A). This caused the heat concentrated in the outlet (B), which made the flame temperature higher than copper.

Copper, which had a higher thermal conductivity than stainless steel, when the combustion occurred, the generated heat was quickly conducted into the inlet (A). This caused the heat unconcentrated in the outlet (B), which made the flame temperature lower than stainless steel.

4. Conclusion

It can be concluded that the flame holder with a higher thermal conductivity has a wider flammability limit than those with a lower flammability limit. Pure copper is not recommended for flame holder application due to the decreasing thermal conductivity when the temperature increases; so, it influences the flame stability of mesocombustor. Meanwhile, flame visualization, in the form of flammability limit extension, was affected by flow velocity while the flame brightness was affected by equivalence ratio. Besides, the temperature of mesocombustor was affected by flow velocity and equivalence ratio.

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