Performance Study of Micro Combustor Utilising Nickel Based Catalyst on Alumina Foam Porous Support

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Abstract. Alumina foam was utilised as a porous medium support for catalyst in a micro combustion process using liquefied petroleum gas (LPG) as fuel. Through wet impregnation method, nickel was deposited onto the surface of alumina foam forming catalytic porous medium for micro combustion. In this study, the performance of micro combustion was investigated corresponding to three main factors based on the flame location, flue gas composition and the efficiency of combustion at lean combustion condition. It was found that combustion process started at ambient temperature produced low composition of SO₂ and NOx for all experimental samples. Results also showed that combustion efficiency increases with the decrease in porosity of alumina foam used, whereby 22 % of porosity gives the highest combustion efficiency. Experiments with the deposition of active material nickel onto the alumina foam also produced similar results, where 22 % porosity of alumina foam gives the highest combustion efficiency. With nickel as active material deposited onto alumina foam, higher combustion efficiency can be achieved, with results from 40 % up to above 70 % combustion efficiency corresponding to the concentration of catalyst loading from 0.1 M to 1.0 M of Ni(NO₃)₂·6H₂O preparation solution. Several advantages using catalytic combustion includes the capability in reducing the impact of thermal and radical quenching, easy start-up, robust to heat loss, low pollution gas emission, and operation at very lean air-fuel ratio condition. It has been found that the use of catalyst using porous alumina support can significantly increase the efficiency of combustion reaction and therefore improve the overall performance of micro combustion.

1. Introduction
Portable electrical devices are very useful and becoming increasingly important in modern daily life usage. They are commonly powered through rechargeable battery technology, which require recharging when energy is depleted. Through micro combustor technology, there is no requirement of energy recharging whereby fuel is continuously supplied to produce continuous energy via small scale combustion. Most of devices such as cellular phones, notebook computers, digital camera and many other electronic device applications required a compact, long lifetime, and instant rechargeable power supplies capable of providing power from several miliwatts to hundred watts [1]. Unfortunately, the most efficient lithium-ion electrochemical batteries have very low power densities (0.2 kW h/kg) compared to hydrocarbon fuel yet require several hours of charging and their life is limited to finite and limited rechargeable cycles [2]. The impact from this drawback is low demand from a category of consumer that need a high performance with long lasting usage. This is where micro combustor would be an attractive option as a viable energy source.
Micro combustor

A micro combustor is a small-scale combustor having combustion chamber normally in the size range of several millimeters. A micro combustor provides electricity by converting chemical energy from combustion process into electricity directly. In recent years, many innovative micro-combustors for propulsion, power generation, chemical sensing, and heating have been designed or under development [1]. However, it was found the use of micro-scale combustor has given several problems. For example, high quenching distance, radical quenching, and uniform temperature distribution, heat loss from high surface to volume ratio, and blow out. Improvement and fabrication on micro combustor is required [7].

This paper is looking on the improvement in combustion processes in micro combustor by incorporating catalyst within a porous medium structure to increase performances in flame stability and combustion efficiency.

2.1. Porous medium combustion

Combustion with porous medium can fulfils the requirements of a certain challenges that need to be addressed such as demand for more efficient, less polluting, and less energy consuming combustion technologies. By using porous medium as catalyst support, it can eventually lower the pollutant emissions, providing higher power density, high turn down ratio, enhanced combustion stability, and the potential to operate in ultra-lean combustion regimes [3].

Figure 1. Schematic diagram of porous medium combustion

2.2. Nickel as catalyst

In this study, nickel-based catalyst was chosen as an active material. Mechanistic findings suggest that cheap and easily available nickel species can be potentially more chemically reactive compared to expensive palladium and platinum species. Moreover, the increasing price of palladium, platinum, and other noble metals even further stimulate the search for inexpensive and easily available catalysts [4]. This provides a remarkable opportunity to develop new nickel catalysts.
3. Material and method

3.1. Surface cleaning process
Raw alumina foam must undergo surface cleaning process to remove any foreign substances that are deposited on the surface of alumina foam. Four different porosity of alumina foam (22 %, 84 %, 86 %, and 91 %) based on manufacturer’s specification were utilised for combustion performance study.

Table 1. List of chemicals and materials used in this experiment

| Chemicals/ Materials          | Chemical Formula | Usage                          | Specification                  |
|-------------------------------|------------------|--------------------------------|--------------------------------|
| Nickel Nitrate Hexahydrate     | Ni(NO₃)₂·6H₂O     | Precursor for impregnation method | 98.5%                          |
| Alumina foam                  | Al₂O₃            | Catalyst support                | Porosity: 22 %, 84 %, 86 %, 91 % |
| Acetone                       | C₃H₆O           | Use for surface cleaning of alumina foam | 99.9%                          |
| Liquefied petroleum gas, LPG  | C₃H₈/C₄H₁₀       | Fuel source                     | Composition: 40 % C₃H₈, 60 % C₄H₁₀ |

3.2. Catalyst preparation using wet impregnation method
Wet impregnation method was chosen for the deposition of nickel onto alumina foam which acts as catalyst support following the method proposed by Liu [6]. For each alumina foam porosity, different concentration of nickel (II) nitrate hexahydrate solution were prepared (0.1 M, 0.25 M, 0.5 M, and 1.0 M) followed by dipping time of alumina foam in the solution for 24 hours. The catalysed-alumina foam samples are dried in an oven at 100°C for 2 hours and then calcined at 500°C for 2 hours with temperature ramp of 5°C min⁻¹.

3.3. Performance test
The experimental set up consists of two digital mass flow controllers, LPG cylinder, a compressed industrial air cylinder, a mixer, a connection tube, and a personal computer [5]. The flow rate of LPG was controlled using Sierra® Smart-Trak 100 Series mass flow controller (Sierra Instruments, USA), whereas the flow rate of air was controlled using Sierra® Smart-Trak 50 Series mass flow controller (Sierra Instruments, USA). Figure 2 shows the photo of actual experimental set up for catalytic micro-scale combustor and Figure 3 shows the schematic diagram of experimental setup. The setup has been described in detailed in previously published work in reference [5]. The micro combustor has a pyramidal geometry entrance to induce uniform flow along and across the catalytic porous medium with dimension of 10 mm × 10 mm × 25.4 mm (length × width × thick) and the micro combustor’s inlet has inner diameter of 1.6 mm and outer diameter of 3.2 mm, respectively.
Figure 2. Actual experimental setup

Figure 3. Schematic diagram of experimental setup

4. Results and discussions
The performance of four different porosity of alumina foam was tested to study the flame location, flue gas composition and combustion efficiency. Based on visual observation during combustion for different porosity of alumina foam without catalyst loaded, all samples showed similar flame behavior, with blue color flame appearing slightly outside of the alumina foam. However, results with presence of catalyst on alumina foam showed slightly less bright flame was observed. Although almost similar flame behavior was observed, it is possible that the slightly less bright flame indicates that the location of the flame tends to be more contained within the porous alumina foam. Nevertheless, the analyses based on visual observation alone is not conclusive to justify the location of flame during experiment. Figure 4(a) shows photo sample of flame for experiment without alumina foam, and Figure 4(b) shows photo of flame for experiment with 1.0 M of preparation solution with alumina foam porosity of 22 %. 
Figure 4. Photo of flame for experiment: (a) without alumina foam (b) with alumina foam

4.1. Micro combustion with porous alumina foam

Figure 5 shows the overall flue gas composition from combustion: (a) without alumina foam, and (b) by using alumina foam with 22 % porosity. For other porosity of alumina foam, results obtained showed similar pattern with 22 % porosity. Referring to Figure 5(a) for combustion without alumina foam, the SO₂ produced was around 10 to 15 volume percent throughout 30 minutes. However, for combustion with alumina foam, only about 5 % of SO₂ was detected for first 10 minutes then almost no amount of SO₂ was detected. This shows that toxic gas SO₂ can be minimized using porous alumina foam, as shown in Figure 5(b).

For NOx detection without alumina foam, it can be seen from Figure 5(a) that the NOx produced is around 5 %. However, the formation NOx can be seen being increased using porous alumina foam, and more significantly increased after 10 minutes of combustion taking place. Although the increase in NOx is not favorable, there is a favorable decrease in CO from maximum 70 % initially to finally about 40 %. It can also be seen that the trend of CO₂ produced is also reduced when porous alumina foam was used.
4.2. Micro combustion with porous alumina foam incorporating catalyst

Figure 6 shows a flue gas composition obtained from combustion using 22% porosity of alumina foam treated with nickel nitrate hexahydrate. By comparing Figure 6 with Figure 5, similar trend is seen and generally, it can be said that the flue gas is more stable in the presence of porous alumina foam. Addition of nickel as catalyst would also have some effect in reducing the CO and CO$_2$ components in flue gas.

4.3. Combustion efficiency of the micro-combustor

Based on the combustion reaction, the efficiency can be obtained and calculated using Siegert’s formula. Table 2 shows result of combustion efficiency for different porosity of Al$_2$O$_3$ foam with different molarity of preparation solution.

Data from Table 2 shows the combustion efficiency is increased with decreasing porosity of alumina foam. Since the lowest porosity of alumina foam was 22% in this study, there might be possibility of increasing further the combustion efficiency if lower porosity alumina foam is used. However, that will be depending on the commercially availability of alumina foam having lower porosity. Also, it would be expected that there would be a minimum value of porosity that could give best combustion efficiency. A very low porosity would mean approaching the non-porosity behavior defeating the purpose of maximizing efficiency based on varying porosity.
Table 2. Combustion efficiency for different porosity of Al₂O₃ foam

| Porosity (%) | Combustion efficiency (%) |
|--------------|---------------------------|
|              | 0.1 M Ni/ Al₂O₃ | 0.25 M Ni/ Al₂O₃ | 0.5 M Ni/ Al₂O₃ | 1.0 M Ni/ Al₂O₃ |
| 22           | 39.54          | 47.40          | 56.73          | 71.39          |
| 84           | 28.83          | 30.71          | 32.38          | 39.96          |
| 86           | 18.22          | 22.37          | 23.75          | 29.93          |
| 91           | 9.58           | 10.36          | 11.74          | 20.69          |

Incorporating nickel as catalyst onto alumina foam can further boost the combustion efficiency of 22 % porosity of alumina foam from 40 % up to above 70 % combustion efficiency, depending on the concentration of nickel nitrate hydrate solution prepared from lowest molarity of 0.1 M to highest molarity of 1.0 M.

5. Conclusions
The performance of micro combustor based on flame stability and combustion efficiency were investigated to study the combustion process by incorporating catalyst within a porous medium structure. Porous alumina foams have been successfully deposited with nickel catalyst with four different molarity of preparation solution through wet impregnation method. The implementation of alumina foam as a porous medium has shown that the micro combustor can reduce the amount of harmful gases emission such as SO₂ and CO. Besides, the combustion efficiency of micro combustor can be further improved by incorporating nickel as active material onto porous medium support. It has been found that among four different porosity of alumina, 22 % porosity gives the highest combustion efficiency, in the presence of catalyst or without catalyst. The combustion efficiency was further improved from 40 % up to above 70 % by incorporating nickel catalyst onto porous medium support. Through wet impregnation method, the output result of highest combustion efficiency was obtained corresponding to highest concentration of preparation solution of Ni(NO₃)₂·6H₂O.

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