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A practical approach in porous medium combustion for domestic application: A review

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Abstract. Combustion in porous media has been widely studied. Many application involving the combustion of porous media has been reported in various way with most consider on numerical works and industrial application. Besides, recent application of porous medium combustion for domestic is the topic of interest among researchers. In this paper, a review was conducted on the combustion of porous media in term of practical application for domestic consumers. Details on the type of fuel used including bio fuel and their system have been search thoroughly. Most of the system have utilized compressed air system to provide lean combustion in domestic application. Some self-aspirating system of porous medium burner was also reported. The application of new technology such as cogeneration by using thermoelectric cells in tandem with porous medium combustion is also revised according to recent work which have already been published. Besides, the recent advances which include coating of porous material is also considered at the end of this paper.

1. Porous media as a medium of combustion

Porous medium can be made from metal, ceramics, plastic or any materials. However, only high temperature resistance materials such as metal and ceramic are suitable to be used as medium of combustion. The selection between porous metal and ceramics materials is based on the application of the burner. Metallic materials have less thermal stability and high thermal inertia. Thus, metal porous materials were less use for porous medium combustion. The porous ceramic are frequently used than metals in porous burners based on the temperature stability produced during combustion with comparatively acceptable emission [1]. The work on combustion using ceramic porous media has been reviewed by Wood and Harris [2]. Recently, several studies have established the applications of porous ceramic inert media in combustion [3-5].

2. Types of fuels used in porous medium combustion

2.1 Gas combustion

In porous medium combustion, gas fuel such as methane, butane, propane and LPG are often used in many applications reported. LPG gas is well known in the domestic gas burner applications, while butane or propane is suitable to be used for portable burners. Combustion by using LPG in porous medium burner have been carried out by many researchers [6-9]. Most LPG combustion in porous medium concentrate on the application for domestic use such as porous medium gas stove [7, 8, 10]. A work by Cerri [11] on porous medium combustion using methane has been conducted on two ceramic foam burners with and without catalytic. It was found that HC concentrations always remained low on both cases. Gao [12] has published a few work on methane and propane gas combustion with latest work by using two layer porous burner with different foam.[13, 14]. There are many others recent works [15-21] using methane as fuel in porous medium combustion describing methane as the most allowable gas source to be produced and used in many ways especially with porous medium burner. Toledo [22] used butane fuel and wood pellets to produce syngas through rich and ultra-rich combustion in an inert porous medium . Propane has also been used [23] to produce hydrogen by using combustion in porous medium. The used of propane for porous medium combustion has been widely tested [24-28].

2.2 Liquid combustion

The combustion of liquid fuel in porous burner is less reported. The use of kerosene fuel in porous burner is tested to suit with domestic burner application normally in rural area where LPG is not available. The problem of using liquid fuel in porous burner is that the liquid fuel need to be vaporized before entering the porous medium reaction zone to produce flame such as in gas combustion. A study of kerosene combustion in porous medium has been done experimentally by Vijaykant [29] using carbon foam with SiC coated. The heat recirculation inside the foam pre vaporizes the liquid kerosene fuel before combustion. It was found that combustion of kerosene in porous medium reduced the emission by improving the vaporization and air fuel premixing. Aviation grade kerosene has been used by Periasamy [30, 31] to study the performance and emission in porous medium combustion. The kerosene was injected by using an air-blast atomizer to produce stable flame. From this study, it has been shown that the NOx produced was not dominated by parameter such as equivalence ratio and spray nozzle when porous medium is used. Latest study on kerosene non-spray combustion in porous medium can be found from work prepared by Wongwatcharaphon [32, 33]. Pastore [34, 35] has provided a study on syngas production through rich combustion of liquid fuel such as n-heptane, diesel oil, kerosene and rapeseed-oil methyl ester (RME) bio-diesel. Combustion of other liquid fuels such as heptane can be found from work performed by Kaplan [36] using a spray nozzle for fuel impingement in porous medium combustion zone. Kamal [37] has studied on the orientation of the spray nozzle in porous medium with swirled air supply. Porous medium which has been inserted at the burner exit has produced droplet evaporation while enlarging the recirculation zone before the fuel injector improving mixing and combustion efficiency. Trimis [38] produced a novel cool flame vaporizer for liquid fuel with porous medium burner. Krittacom [39] investigated the evaporation of diesel fuel and its combustion behavior. The fuel drop technique was used. The porous burner (PB) used pebbles with and without porous emitter (PE) where higher temperature profile has been found for PB with PE. More works can be found from literatures provided by Jugjai [40, 41] without using spray atomization for liquid porous medium combustion. Heavy oil or crude oil combustion in porous medium has been studied by Cinar [42].

2.3 Bio fuel combustion

A few recent work have covered on the use of vegetable cooking oil–kerosene fuel blends for porous burners. The burners are designed for domestic application which involved heat generation for cooking as well as power generation by using thermoelectric and thermophotovoltaic cells [43-45]. In this study, comparison has also being done. The test includes different mixtures blend composition of kerosene-vegetable cooking oil (VCO) such as: 100 kerosene, 95/5 KVCO, 90/10 KVCO, 80/20 KVCO, 75/25 KVCO and 50/50 KVCO. The power output was found to be increased in lean region with lower emission. However, these values started to increase beyond the stoichiometric ratio. Renewable energy source such as bio fuel become significant nowadays. By taking advantages of porous medium combustion, the use of bio fuel can be more efficient. The type of bio fuel that is currently tested in porous burner is vegetable oil [46]. There are bio fuel in liquid form such as blended kerosene fuel with palm oil or bio seed fuel. BIOFLAM project [47, 48] used renewable biodiesel which is also known as a Fatty Acid Methyl Ester (FAME). In this project, a specially designed ceramic premixed liquid fuel porous medium burner was used with cool flame vaporization technique to produce high power modulation with low emission level. In another work, vegetable (rapeseed) oil as a bio fuel has been tested with porous medium combustion [49]. A prototype integrated vaporizer system with a PIM burner based on the flow velocity flame stabilization technique was built and investigated. A stable combustion has been observed with the absence of CO emissions recorded. Canola methyl ester (CME) and soy methyl ester (SME) produced from vegetable were among the bio fuel tested in porous medium burner [50]. It has been found that the axial flame temperature produced by CME and SME were similar to commercial Jet-A fuel combustion in porous medium burner. However, some clogs were found due to solid particle decomposition stuck in porous medium and on the metal walls of the injector by combustion of CME and SME. Biogas is another type of renewable energy that can be used with porous medium burner. Due to the low heating value of biogas, the Reciprocal Flow Porous Burner (RFPB) has been used by [51] to increase the efficiency with low emission. A stable combustion was found for both study of methane and biogas combustion, when RFPB is applied, which is also more efficient having low emissions. Some interesting studies related to the used of biogas in porous medium combustion can be found from the work done by Gao and Keramiotis [52, 53].

2.4 Exhaust gas emission from porous medium combustion

The incomplete combustion of fossil fuel which is also known as hydrocarbon (HC) fuel produced unburned hydrocarbon (UHC) and carbon monoxide (CO). Another product of combustion which is dangerous is the nitrogen oxide gas or NOx. This type of gas will only occur at very high temperature where the nitrogen content in the atmospheric air oxidized in combustion flame. Whereas, high temperature combustion crack down the CO into CO_2 in atmospheric air as well as promoting the UHC to be completely burned. Therefore a trade of between CO and NOx in HC fuels existed**.** The strategy of using porous medium to cater with the trade off issue between CO and NOx has been found by Trimis [54]. By using porous medium, the combustion of HC fuel will be completely burned inside the porous media without leaving any UHC. High temperature combustion flame has been controlled by the use of porous medium and the nitrogen gas oxidation will not exist in the surrounding air avoiding the formation of NOx. A numerical study has been done by Zhou [55] to investigate the NO and CO emission reduction in porous medium . Due to very high temperature inside porous medium solid material, the heat transfer mechanism to the thermal load will be largely due to radiation mode which will not oxidize the nitrogen gas in the air. This phenomena can be found from studies on porous medium radiant burner where CO and NOx were both in relatively low and in acceptable range [36]. By manipulating the pressure and temperature of the inlet mixture into porous medium combustion system, the CO can be eliminated and NOx content was remarkably reduced as studied by Bakry [56].

3. Recent application of porous medium combustion devices

Numerous application of porous medium in combustion devices has been found. Some recent works on major application has been selected to describe the essential of porous medium combustion technology. Water purification is one of the examples of using porous medium combustion technique [57] [58]. A new technology of water purification of organic inclusions or solutes by using a filtration combustion reactor with alternating flow direction is investigated. An acetone aqueous solution served as a model liquid. Non-catalytic porous burner also can be used in syngas production as presented by Pastore [34]. A two-layer inert porous medium combustor was used and different fuels such as n-heptane, diesel, kerosene and bio-diesel were successfully reformed to syngas in a Zirconia foam burner with conversion efficiency over 60%. Micro heat-recirculating combustor using porous media plate, has been designed and tested by Cao [59]. The micro heat-recirculating combustor has a very important application value in developing the micro gas turbine power generation system. The micro porous media combustor possesses some merits such as wider combustion operation ranges, higher combustion efficiency and lower heat loss ratio and should be an ideal micro combustor for developing the micro gas turbine power generation system [60]. **S**tability of lean combustion in mini-scale porous media combustor with heat recuperation was studied by Xu [24]. In miniaturization of burners, it is very difficult to organize stable self-sustained combustion. A mini-scale porous media combustor with heat recuperation was set up to study the stability of lean combustion and its emission. The diameter of the porous media was only 20mm and the burner was about 140mm in length.

3.1 Domestic porous medium burner

Some attempts have been found to produce domestic porous medium burner especially on gas stove. A concept of Porous Radiant Re-circulated Burner (PRRB) has been introduced by Jugjai [61]. The PRRB re-circulated the exhaust gas captured by porous medium to preheat the incoming secondary air supply. Muthukumar [7] presented a detail study on LPG gas stove using porous medium technology in line with Pantangi [62]. However, the design of the stove needs improvement taking into account the application of porous medium burner without compressed air. A practical self-aspirating porous medium burner has been developed and tested by Yoksenakul [63] using LPG. This porous medium burner has been designed according to the allowable Peclet number calculated from Ergun equation on pressure losses. The burner has demonstrated stabilized flame with surface and submerged combustion flame without flashback. The use of packed bed with sphere balls has reduced the pressure drop for this naturally aspirated porous medium burner. However, the results of CO emission are higher compared to conventional burner (CB) with a small improvement in thermal efficiency. Another domestic application of porous medium burner is the heat production for household application [64]. This burner is capable for use in water heating by adopting customized heat exchanger.The use of porous ceramic foam in premixed porous medium LPG stove can be found from the work performed by Mujeebu [10, 65, 66]. Two different foams have been used to create preheater and reaction zone by using Alumina and Porcelain types of ceramic. The thickness of the foam has been studied to find the best thickness which provides better flame combustion, emission and flame stability. Porous radiant burner (PRB) was study by Pantangi [8]. The PRB was developed for domestic cooking stove by using LPG. PRB consist of SiC reaction layer and alumina balls preheating layer. Performance test has been done by using the water boiling test according to BIS (Bureau of Indian Standard) to compare the efficiency between PRB and conventional burner (CB) of cooking stove. It has been found that the PRB has higher efficiency of about 3% over CB. Lower CO and NOx is also detected for PRB compared with CB.Since most domestic burners operate by self-aspirating air supply system, the application of this type of burner with porous medium combustion technique continuously investigated. Laphirattanakul demonstrated on porous medium combustion with self-entrainment system [67]. The system concentrated on naturally aspirated air supply system which include primary and secondary natural draft. Different flame images have been compared at different thermal power output to investigate the combustion stability and propagation. This work has shown detail explanation on the direction of heat from flame propagation which gives advantages for the design of naturally aspirated porous burners which can also extend to the combustion model in numerical analysis.

3.2 Application of Thermoelectric and Thermo Photovoltaic for cogeneration

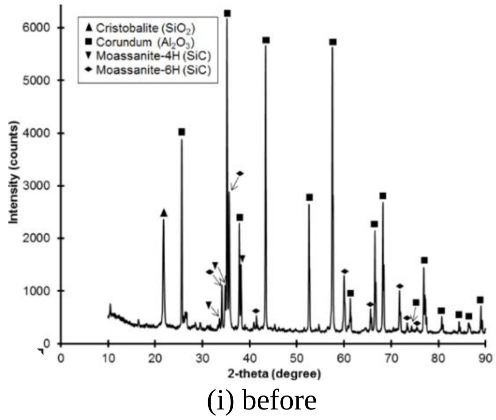
An experimental study has been carried out [68] on the use of a power-generated system with TE cells to generate electrical power for household use. Champier [69] applied the TE cells to their biomass cook stove for power cogeneration in rural areas. A portable power source using butane as fuel for heat power conversion by TE cell has been done by Posthill [70]. SiC coated porous medium foam has been used for thermoelectric power conversion by Mueller [71]. A few works on patent burners involving TE generator can be found from Cedar and Hu [72, 73]. An attempt on combining the TE and TPV to enhance the thermal efficiency with higher power generation has been done by Sark [74] while Yang [75] proposed novel design of combining TE, TPV and hot water (HW) for solar power generation. Latest work conducted by Singh [76] provide study on small scale burner with self-aspirating system to be used for power generation. This system is said to produce continuous electrical power output for a long period by stabilizing the combustion process. For this study, thermoelectric devices were used for power generation with also considered on the environment condition which includes ambient temperature. From the effort published, it is found that the power generated from small scale heat source or domestic burner is crucial nowadays especially to be used for outdoor and at rural areas with the absence of electricity. Detail layout and photographic views of the porous medium burner with cogeneration by Ismail et.al [77] described the latest application of porous medium burner for heating and power generation system.

4. Effect of coating to the porous medium combustion

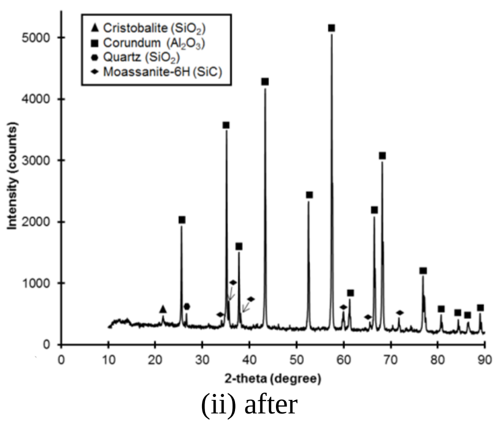
The used of coating techniques on porous medium for combustion was less reported. Materials such as SiC, Ni and Cr were selected due to the catalytic capabilities. These catalytically active materials were usually employed to improve the properties of combustion process. It is known that noble metals such as gold and platinum provide high catalytic activity, and are very good medium for combustion reactions. However these noble metals and its compounds are expensive, and it may experience sublimation when use at high temperatures. SiC which is a type of ceramic is also known to have thermal stability and chemical inertness as well as can be used as catalyst material. Therefore, these transitional metals (Ni and Cr), and SiC have been chosen and the coating technique was by using dip-coating method onto an inert Al_2O_3 porous substrate [78, 79].

For coating techniques, the plain substrate was initially prepared. Then, the sintered plain substrate is dipped in the coating bath (coating slurry) and re-sintered to obtain a uniform coating. A liquid deposition method was used to coat the SiC, Ni, and Cr-based coating slurry on the pre developed plain substrate. This process is also known as the dip-coating technique and is ideally suited for coating porous substrates having highly reticulated structure. In this process the dry plain substrate is first dipped into the coating slurry and after being withdrawn from this solution, results in a wet, dense and uniform coating on the surface of the substrate. As a conclusion, SiC coated Alumina have very less effect on the structure even after used for combustion.

In Fig.1.(i) results prove that during coating process, the coated substrate was not subjected to or experienced very little oxidation and phase changes during the sintering process using the vacuum furnace. The results after combustion in Fig. 1.(ii) shows only the occurrence of moissanite-6H (ICDD: 01-072-0018) phase on the SiC-coated substrate. Other results from the work by Ismail [78] shows that Ni-coated substrate undergoes an obvious oxidation reaction. Moreover, the XRD result for Cr-coated porous substrate also show an oxidized coating layer indicated by the presence of chromium oxide phase after the combustion test. As a conclusion, SiC coated Alumina has very less effect on the structure even after used for combustion.



(i) before



(ii) after

Figure 1. XRD patterns of porous Al2O3 substrate coated with SiC (before and after used for medium of combustion)[78]

5. Conclusion

Domestic porous medium burner has been intensively studied which most considered on the small scale burners and self-aspirating system. Based on the application of thermoelectrics and thermophotovoltaic for power generation in previous work, the application with porous medium burner can be realized. This type of porous burner which is used for domestic is very useful both for indoor and outdoor activities when necessary for electrical power output and heating purposes. The use of different fuels for porous medium combustion enhanced the combustion efficiency with less emission produced. Recent advances of domestic porous medium burner considered on many aspects including geometrical and different coating materials of porous medium to be used in combustion. The effect of coating on porous medium combustion has not been focused in previous work. This may reduce the cost of using purely catalytic materials as porous foam. The use or alumina as porous medium can be much improved with coating techniques.

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