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Research Paper

Developement of porous media burner operating on waste vegetable oil

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HIGHLIGHTS

- Steam was successfully applied to promote combustion of WVO.
- A specially designed porous domain was an essential element for stable combustion of WVO.
- The performance of WVO burner was in the range of cooking stove.
- Nozzle clog up in domestic WVO burner can be avoided when replacing it with a steam-assisted nozzle.

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ABSTRACT

A newly designed cooking stove using Wasted Vegetable Oil (WVO) as fuel was introduced. Porous media, containing 2 cm diameter of spherical ceramic balls, was used as a flame stabilizer. Steam was successfully applied in a burner at this scale to atomize WVO droplet and entrain air into the combustion zone as well as to reduce soot and CO emission. DIN EN 203-1 testing standard was adopted and the experiment was conducted at various firing rate with the water flow rate at 0.16, 0.20 and 0.22 kg/min. Temperature, emissions, visible flame length, thermal efficiency as well as combustion efficiency were evaluated. Under the current WVOB design, it was suitable to operate the burner at the range of nominal firing rate between 325 and 548 kW/m^2 with water flow rate of 0.16 kg/min, at burner height to diameter ratio of 0.75, giving CO and NO_x emissions up to 171 and 40 ppm, respectively (at 6% O_2). Thermal efficiency was at around 28% where the combustion efficiency was approximately at 99.5%. The performance of WVO burner could be improved further if increasing the H/D ratio to 1.5, yielding thermal efficiency up to 42%.

1. Introduction

Over the last decade, Thailand could not sufficiently produce LPG for its glowing demand. LPG has been widely used in industrial, transportation, residential and commercial sectors, etc. The import of LPG has been increasing. In general, LPG is consumed at about 40% of all domestic energy consumption. Facing the crisis of imported energy, it is important to look for self-sufficiency. One of the solutions is to find an alternative source of energy and efficiently use it. It makes more sense to consider renewable, carbon neutral fuel source derived from biomass. The used vegetable oil (WVO) from cooking process is an interesting source of energy because the heating value remains high at about 36 MJ/kg. In addition, Thailand has the WVO at about 74.5 million L/year, 63.4% come from household uses. Vegetable oil and WVO can also be safely used as fuel with typical diesel engine by transforming it to bio-diesel. However, producing a bio-diesel from WVO need additional heat source during the transesterification process that has more spending cost [1].

Using WVO as a substitution to LPG in domestic cooking process is an interesting choice. Apparently, the direct benefit is the reduction of LPG consumption. Consequently, WVO can be eliminated after cooking, avoiding the risk of consuming toxic element from WVO. To achieve this, a specific burner must be developed. With this type of burner, the mixing of air and fuel must be good within the premixed zone in order to achieve efficient combustion. The ignition must be stable at the designated location throughout the desired operation range. The retention time of flue gas mixture in the combustion zone must be long enough to eliminate soot generated at the early stage of combustion [2]. All these challenges must be overcome even at high turn-down ratio, while the technology must be simple to minimize the initial and operation cost.

High pressure atomization [3] was the early technique used for enhancing the rate of vaporization of liquid fuel with high vaporizing temperature like WVO. This was equipped with fuel preheating unit. A special atomization gun was developed [4] so that the oil particle was so small and highly dispersed leading to enhanced

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Nomenclature

W_{water}	mass of water in the container [kg]
W_{vapor}	mass of water vapor generated during test period [kg]
ΔT	temperature difference of water [°C]
$\dot{m}_{fuel}$	mass flow rate of oil used [kg/s]
LHV_{WVO}	lower heating value of WVO [kJ/kg]
$h_{fg,vopour}$	latent heat of vaporization [kJ/kg]
t_{total}	total period of time in each experiment [s]
$Cp_{,water}$	specific heat of water [kJ/kg K]
$[Emission]_{6\%}$	emission at 6%V/V of O_2 in flue gas
$[Emission]$	emission taken at the hood (%V/V, ppm)
$[O_2]$	oxygen concentration(%V/V)
E_f	heat throughput of the combustor with incoming fuel [kW]
E_{CO}	energy leaving the combustor in the form of enthalpy of formation of CO [kW]

combustion efficiency and increase in turn-down ratio. However, these devices had suffered significantly from fuel impurities as it was operated on a principle of flow passing small orifice. Alternatively, a rotating cup [5] was developed for the same purpose. With this technique the oil liquid was spread into thin film by centrifugal force and spilled away from the disk in the form of small droplet. This later technique however, required relatively more sophisticate components and exhaustive mechanical energy during operation. It had therefore been adopted in large combustion system and not appropriate for a small device. As mentioned earlier, oil with high viscosity could be atomized with the aid of preheating unit. It had been adopted and developed further by installation of the atomizer and vaporizer in the combustion chamber [6] so that the heat from combustion shall be used for preheating and vaporizing purpose. These ideas, together with the nozzle-type atomizer were later adopted for the first version of WVO burner [7] with fuel-air premixed combustion chamber. The disadvantage, however, was found stemming from severe operating condition of the vaporizer as the material could not stand for high temperature within required period of operation. Combustion stability was also hindered by the continuity of oil injection pressure and heat transfer rate to the vaporizer unit. Furthermore, the deposition of solid carbon generated during thermal decomposition of WVO vapor had caused the blockage at the nozzle hole, the mechanism can be illustrated in Fig. 1.

In the last decade, many researchers in the field of burner development had adopted porous materials on their works due to their remarkable advantages. These led to improvement of combustion efficiency. The circulated heat through the porous matrix, by thermal radiation and conduction schemes, yielded excess enthalpy back to the reactant which led to super adiabatic flame. It produced higher peak temperature than the "standard adiabatic flame" obtained under the conventional condition [8–12]. Applications of porous materials on liquefied fuels can be found in various ways, such as using them as a liquid fuel atomizer to generate the liquid fuel droplet and as a vaporizer.

Kaplan et al. [13] investigated the combustion of kerosene inside porous medium, expecting to reduce the NO_x, CO and soot emissions. Silicon carbide (SiC) coated by carbon foam was used as Porous Media (PM) to enhance the high strength structure. Three combustor operating regimes depending on an injector location were observed. Firstly: (a) an injector was placed on far upstream of PM, so fuel was pre-vaporized and well-premixed with air leading to homogenous reactant mixture. Secondly, (b) an injector was placed at intermediate region between the location in (a) and PM causing pre-vaporization of fuel. And finally, (c) an injector was located close to PM, thus the resident time was insufficient for evaporation and mixing prior to combustion. This had resulted in residual fuel in droplet form and diffusion flame was observed. Comparing between the three cases, (a) produced the lowest emissions, while (c) was the highest. Apparently, the emissions, i.e.; CO, NO_x and soot, were significantly increased from (a) to (c). Kaplan and Hall used three types of porous ceramics namely magnesia-stabilized zirconia, silicon carbide, and yttrium-stabilized zirconia. Heptane, as fuel, was impinged on the combustion section by using the pressure atomizer. It was found that complete combustion was achieved within the equivalent ratios of 0.57–0.67. CO emission was varied from 3 to 7 ppm and NO_x also was from 15 to 20 ppm based on 3% of O_2.

Takami et al. [14] attempted to continue the previous work of Tseng and Howell [15] by developing the liquefied fuel porous ceramic burner without using a fuel atomizer. In their experiment, droplets of Kerosene were discovered on top of the horizontal porous ceramics plate. Flammable condition was found at minimum equivalent ratio of 0.1. The maximum turn-down ratio was 5.8 with nominal firing rate of 670–3880 kW/m^2.

The advancement in porous combustion was stepped further by Jugjai et al. [16] by considering more details on evaporation mechanism inside porous burner. They focused specifically on the introduction of a packed bed emitter downstream of the porous burner. By adjusting the parameters including heat input and equivalent ratio, the result of combustion performance had definitely confirmed that the mixing of fuel vapor/air was improved and the turned-down ratio could be increased under porous media application. It was also found that the introduction of packed bed emitter was an efficient method for enhancing evaporation and combustion in liquefied fuel without a spray atomizer. Again in 2007 Jugjai and Pongsai [17] presented a similar type of experimental study on the so-called "Liquid fuel-fired porous combustors" (LFFPC).

The significant problem usually found on liquid fuel operating with insufficient air is the formation of soot. One of solutions is to inject superheated steam into the combustion zone. The hydrogen components in water molecules will react with the carbon components in fuel. It is called Water Gas Shift Reaction. There has been a number of works studying on this effect on emission. For instant, Robert et al. [18] designed the liquid fuel operating burner with steam injector. The low pressure steam was injected through a small hole in order to create inducing force that entrains the surrounding air into the combustion chamber. They also adjusted the weight fraction of steam and fuel. It had also been proven that the steam injection technique was capable to decrease

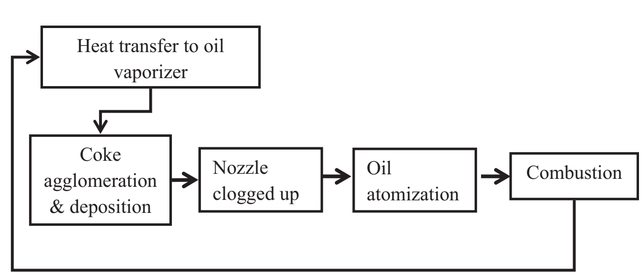

Fig. 1. Thermo/mechanical mechanism for pressure atomization of vegetable oil.