Fuel 119 (2014) 240–251

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Investigation on boiler efficiency and pollutant emissions of water/heavy oil emulsions using edge-tone resonant homogenizer

Yi-Yin Li [a,b], Shuhn-Shyurng Hou [c], Wen-Jenn Sheu [a,*]

[a] *Department of Power Mechanical Engineering, National Tsing Hua University, 101, Section 2, Kuang Fu Road, Hsinchu 30013, Taiwan, ROC*
[b] *Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Hsinchu 31040, Taiwan, ROC*
[c] *Department of Mechanical Engineering, Kun Shan University, Tainan 71003, Taiwan, ROC*

HIGHLIGHTS

- No surfactant is necessary in the edge-tone homogenizer.
- This homogenizer can produce water droplets with the micro-meter size.
- The W/O emulsion with 14% water content has 15% of energy saving.
- Lower CO emissions are found for the boiler firing W/O emulsions.

ARTICLE INFO

Article history:
Received 25 August 2013
Received in revised form 28 October 2013
Accepted 14 November 2013
Available online 4 December 2013

Keywords:
Heavy oil
Water-in-oil emulsion
Homogenizer
Edge tone
Boiler efficiency

ABSTRACT

Water/heavy oil emulsion prepared by an edge-tone resonant homogenizer without a surfactant is investigated. The three aims of this study are: (1) the spectrum analysis of pressure vibration inside the resonant chamber of the homogenizer, (2) the production of droplets with the desired mean size and a suitable distribution, and (3) the determination of the boiler efficiency using a thermal input–output method. The homogenizer is designed to generate resonant vibrations through the interaction between the jet exit and a knife-like blade under the conditions of high temperature and pressure. The desired mean droplet size (on the order of micrometers) and the proper size distribution for the water/heavy oil emulsion are achieved using the homogenizer. It is found that the amplitude of pressure fluctuation is at its maximum at the first-stage resonant frequency. The boiler efficiency calculated using the thermal input–output method shows that the water/heavy oil emulsion has the potential to reduce energy consumption by 15% compared to that obtained with pure heavy oil. The NO_x emissions in the boiler furnace increase with increasing amount of excess air. Additionally, lower CO emissions are found for the boiler firing water/heavy oil emulsions because of the occurrence of micro-explosion, also known as secondary atomization.

1. Introduction

Liquid fuel remains the primary energy source due to its high energy density and ease of use. With increasing crude oil prices, alternative liquid fuels, including heavy oil, emulsion oil, and pyrolysis oil, have received increased research interest. Emulsion oil is a mixture of base fuel and water with a small amount of surfactant added to overcome the immiscibility between water and oil, allowing the two substances to temporarily dissolve. A water/oil emulsion, generally called a two-phase emulsion, is usually classified as either water-in-oil (water/oil, W/O) type or oil-in-water (oil/water, O/W) type, depending on the hydrophilic–lipophlilic balance (HLB) of the surfactants (emulsifiers) [1]. W/O emulsions have been used as an alternative fuel for diesel engines, boilers, and incinerators to improve fuel economy and reduce pollution [2,3].

1.1. Water/heavy oil emulsions and micro-explosion

Heavy oils contain high-molecular-mass organic structures within which inorganic functionalities are inserted [4]. Emulsion oil is a mixture of base fuel as a continuous phase and a small amount of water with or without a surfactant as a dispersed phase. The fuel type, water content, density variation with temperature, droplet size of the dispersed phase, and surfactant type can affect the combustion and emission characteristics of emulsions. The major physical properties of water/heavy oil emulsions are density, viscosity, and calorific capacity. The former two properties increase with increasing water content, whereas the latter decreases. The low calorific capacity of emulsions mainly affects the effective

---

* Corresponding author. Tel.: +886 3 5162099; fax: +886 3 5722840.
E-mail address: wjsheu@pme.nthu.edu.tw (W.-J. Sheu).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.11.029

power of internal combustion engines and the efficiency of industrial boilers. These quantitative measures differ between studies due to a lack of universal performance standards. The chemical compositions of emulsions include water (H_2O), carbon (C), hydrogen (H), nitrogen (N), chlorine (Cl), sulfur (S), and oxygen (O). Any variation in the fuel composition directly affects the performance of the combustion system, such as the boiler efficiency and flue gas concentration. The viscosity and surface tension of pure heavy oil and water/heavy oil emulsions decrease with increasing heating temperature and decreasing water content.

With a small amount of surfactant added to overcome the immiscibility between water and oil, fuel–water substances can be temporarily dissolved. Because there is a difference in volatility between fuel and water and the boiling point of water is lower than that of oil, water–fuel emulsion droplets exhibit explosive evaporation through the surrounding oil layers. These explosions induce secondary atomization, producing a number of fine secondary droplets [5]. Micro-explosion, also known as secondary atomization [5], enhances the mixing of fuel and air during combustion and thus improves combustion efficiency and reduces pollutant emissions. In general, a suitable surfactant is required to reduce thermodynamic instability, surface tension, and interfacial free energy between water and fuel [1]. Little is known about the properties of surfactant-free water/heavy-oil emulsions [6], from which water droplets do not separate.

1.2. Edge-tone homogenizer

There are three mixing processes of water/heavy oil emulsions, namely the preparation process, the combustion process, and the post-combustion process. When fuel and water with or without an emulsifier are mixed in the preparation process, the dispersed water droplet phase becomes wrapped in a continuous oil phase by external forces, such as mechanical stirring or ultra-sonication. Mechanical stirring destroys the interfacial tension between the continuous phase and the dispersed phase and breaks up water into small droplets. Due to the large shearing and cutting force against the emulsification between oil and water, mechanical homogenization is commonly used for emulsion preparation in industry.

The application of the ultrasonic vibration method, which is widely used in the food, biochemistry, and medical industries, to the preparation of water/heavy oil emulsions is increasing. Ultrasonic emulsification can be designed to be a continuous process of emulsion preparation, making it efficient and fast. Although the mixing and homogenization processes only slightly affect the density of emulsions, the values of viscosity and surface tension change with the distribution and size of dispersed water droplets. The stability of emulsions increases with homogeneity. Fuel and water are mixed but remain separated as two discrete phases. When water/heavy oil emulsions are used in the combustion process, additional jet momentum is achieved because the mass of water is higher than that of pure heavy oil. The additional momentum can increase the atomization momentum and the amount of mixed entrained air [3]. In addition, the occurrence of micro-explosion can be considered to be a secondary atomization process through which finer droplets can be produced and the mixing process can be improved [7–11]. During the evaporation or combustion process, the dispersed water in an emulsified fuel droplet can reach a superheated temperature. The superheated state is a thermodynamically meta-stable condition, resulting in micro-explosion and puffing, which is water vapor being blown out from the surface of fine droplets [12–14]. In the post-combustion process, the heat absorption by water vaporization decreases the local adiabatic flame temperature, and thus reduces the chemical reaction rate of thermal NO production in industrial heavy-oil boilers or furnaces [2,10,11,15].

1.3. Periodic self-sustained oscillation

The present study examines the preparation of a large amount of W/O emulsion without a surfactant, focusing on the resonant pressure fluctuation induced by edge-tone flow instability. Heavy oil contains high-molecular-mass organic structures within which inorganic functionalities are inserted [10]. The edge tone is a fluid-dynamic oscillation through the interaction of a jet with a wedge-shaped obstacle [8]. Despite its geometric simplicity, the edge tone displays remarkably complex behavior. A typical edge-tone configuration consists of a plane jet and an encountered wedge (traditionally called the edge) downstream of the jet exit. The oscillatory behavior of the jet results in positive fluid-dynamic feedback based on the unstable shear layers of the jet flow and is amplified by the feedback loop into coherent vortices. This vortex shedding interacts and radiates acoustic waves that are fed back upstream in the jet-edge system.

An edge-tone homogenizer produces violent ultrasonic waves at high frequency and creates cavitation, which leads to alternating positive and negative pressure waves. Therefore, periodically self-sustained oscillation is produced, creating acoustic waves via this positive feedback mechanism. There are two types of oscillation feedback loop, mainly depending on the Reynolds number (Re). For lower values of Re, a hydrodynamically direct feedback loop (edge-tone-like) is generated, whereas for larger values of Re, an indirect feedback loop (organ-pipe-like) is coupled with the resonances of the self-sustained flow. The flow seems to be laminar at small perturbations where a breakdown and separation of the laminar flow occurs because of the growing instability, i.e., an upstream small perturbation of the jet, finally resulting in vortices on both sides of the wedge. The oscillation frequency (f) is greatly influenced by the jet mean exit velocity (U) and the stand-off distance from the jet exit to the blade (w), which can be expressed as [11]:

$$f = C_{freq} \frac{U}{w^n} \tag{1}$$

where C_{freq} is a constant, which depends on two primary factors, U and w, and a number of secondary factors, such as the exit velocity profile, the shape of the nozzle, the sharpness and the transversal position of the edge [11]. A recent study has suggested that the magnitude of n should be unity [11]. If either U or w is changed continuously, the frequency f also changes continuously within a certain range. However, at certain values, the frequency suddenly jumps. The continuous ranges are called stages or hydrodynamic modes.

Without acoustic resonance effects, self-sustained oscillations are created by a direct or hydrodynamic feedback loop (edge-tone-like); the distortion of the vorticity on flow impingement is fed back upstream where new disturbances are induced at the separation location. The acoustic resonance creates an indirect feedback path and reinforces the level of the self-sustained oscillations and their frequency. The frequency f also depends on the Strouhal number (S_d), which is related to the height of the jet d and w [13].

Flow-excited acoustic resonance is excited by an unstable separated flow that includes a jet, a shear layer, and a bluff-body wake for the above applications. The excitation mechanism consists of a fluid resonance mechanism and a fluid dynamics mechanism. For the former, the resonant sound field is excited by the unstable flow at its separation location. A self-sustained oscillation of impinging shear flow is generated and a new disturbance is produced at the upstream separation location for the latter case [16]. An edge-tone