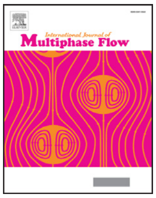
International Journal of Multiphase Flow 85 (2016) 267–277

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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



Cold flow experiments in an entrained flow gasification reactor with a swirl-stabilized pulverized biofuel burner

Burak Göktepe[a,1,*], Ammar Hazim Saber[b,c], Rikard Gebart[a], T. Staffan Lundström[b]

[a] Energy Engineering, Division of Energy Science, Luleå University of Technology, 971 87 Luleå, Sweden
[b] Division of Fluid and Experimental Mechanics, Luleå University of Technology, 971 87 Luleå, Sweden
[c] Mechanical Engineering Department, Mosul University, Mosul, Iraq

ARTICLE INFO

Article history:
Received 22 July 2015
Revised 12 April 2016
Accepted 22 June 2016
Available online 23 June 2016

Keywords:
Biomass
Swirl-stabilized burner
Particle image velocimetry
Particle-laden turbulent flow and entrained flow reactor

ABSTRACT

Short particle residence time in entrained flow gasifiers demands the use of pulverized fuel particles to promote mass and heat transfer, resulting high fuel conversion rate. The pulverized biomass particles have a wide range of aspect ratios which can exhibit different dispersion behavior than that of spherical particles in hot product gas flows. This results in spatial and temporal variations in temperature distribution, the composition and the concentration of syngas and soot yield. One way to control the particle dispersion is to impart a swirling motion to the carrier gas phase. This paper investigates the dispersion behavior of biomass fuel particles in swirling flows. A two-phase particle image velocimetry technique was applied to simultaneously measure particle and gas phase velocities in turbulent isothermal flows. Post-processed PIV images showed that a poly-dispersed behavior of biomass particles with a range of particle size of 112–160 μm imposed a significant impact on the air flow pattern, causing air flow decelerated in a region of high particle concentration. Moreover, the velocity field, obtained from individually tracked biomass particles showed that the swirling motion of the carrier air flow gives arise a rapid spreading of the particles.

1. Introduction

There is currently a large interest in Europe for the conversion of biomass to sustainable and CO_2-neutral motor fuels. With a conservative assumption about the conversion efficiency of 50% from biomass to methanol and utilizing biomass gasification and with biomass potential data from the EU project Biomass Futures (Elbersen et al., 2012) the fuel methanol production potential can be estimated to be of the order of 125–160 MToe (million tons of oil equivalent) per year if all the potential sustainable biomass is used. This corresponds to more than 1/3 of current fossil fuel consumption for transport in the EU and more than 50% of the estimated fuel needs in 2030 (estimated to be 230 MToe/year). Thermal gasification followed by catalytic conversion of the resulting syngas (a mixture of CO, H_2, CO_2 and other compounds) into advanced biofuels, is one of the key processes since it has a high tolerance to variations in the feedstock and a high flexibility with respect to the end products. In order to avoid deactivation of the catalysts it is of utmost importance to have an ultra-clean syngas (Rostrup-Nielsen and Christiansen, 2011). Pressurized entrained flow gasification (PEFG) has been proven in coal gasification to yield a high purity syngas (Higman and Tam, 2014) and the experience with PEFG of biomass, although limited, has also been encouraging (Öhrman et al., 2014; Qin et al., 2012; Weiland et al., 2013).

One of the keys to successful implementation of PEFG is how the fuel and oxidant are introduced and how the flame is stabilized in the gasification reactor. A common concept is to use a controlled amount of swirl that modifies the flow in the reactor to produce a significant recirculation of hot reaction products that can participate in the gasification process to the flame zone. Previous studies in isothermal turbulent jet flows have quantified the influence from swirl on jet growth, rate of entrainment and rate of decay of the jet (Froud, 1995; Huang and Yang, 2009). However, strong swirl flows can also be detrimental to the gasification process by inducing strong flame instabilities, leading to an excessive heating of the burner components by a large mass of recirculating hot gases. Hence, it is important to optimize the strength of swirl with respect to efficiency and operational safety. The relative strength of swirl imparted on the flow is characterized by a non-dimensional parameter, the swirl number. The swirl number, S is defined as the ratio of axial flux of angular momentum to axial

---

[*] Corresponding author.
E-mail address: burak.goktepe@ltu.se (B. Göktepe).
[1] SP Energy Technology Centre, Industrigatan 1, 941 28 Piteå, Sweden

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.06.016
0301-9322/

flux of axial momentum divided by a characteristic radius (Lucca-Negro and O' Doherty, 2001)

The presence of dispersed solid particles of biomass in the gas increases the complexity of turbulent swirling flows through the influence from interaction between phases, the surface irregularities and the clustering tendency of particles. The mass loading ratio, ϕ_m defined as the ratio of the mass of particles to that of the gas phase (DI GIACINTO et al., 1982) indicates the extent of these interactions between phases. The mass loading ratio of the particles influences both the mean and instantaneous gas-phase flow field (Fan et al., 1992, 1990; Gui et al., 2010; Sommerfeld and Qiu, 1991; Zhou et al., 2000).

Entrained flow coal reactors typically use powdered solid particles with a diameter of less than 100 µm to enhance the mass transfer and transport in gas flows (Higman and van der Burgt, 2008). Typically, the milling process that is used to fractionate the biomass to particles results in a wide distribution of size and shape parameters (non-sphericity, surface area, length to width ratios etc.). Unlike coal particles, biomass particles are large, irregular and non-spherical in shape with large aspect ratios, due to their fibrous nature and their high specific energy consumption for milling. For turbulent flows with non-spherical particles of irregular shapes the particle dispersion characteristics and velocity profiles can be significantly different than for the case with spherical particles (Black and McQuay, 2001). Some experimental studies (Capone et al., 2014; Qi et al., 2015) have been conducted with rod-like shape particles, for an improved understanding of the transportation of fibrous particles in turbulent air jet flows. Unlike spherical particles, the regular shaped fibrous particles strongly modulated the mean flow field due to their strong coupling between rotational and translational motion (Capone et al., 2014). A comprehensive numerical study has been conducted to predict the behavior of interacting regular shaped non-spherical particles (sphere, disc, fiber and two types of elipsoids) with large Stokes number in turbulent air flows (van Wachem et al., 2015). According to the model, non-spherical particles move faster than spherical particles and the elongated fibers show the least stable behavior in a turbulent channel flow.

Moreover, large biomass particles impose some limitations to the efficiency of the system. Numerous numerical studies on co-combustion of pulverized coal with biomass in different boiler scales have already highlighted the effect of biomass shares on the boiler efficiency (Bhuiyan and Naser, 2015a, 2015b). In those studies, the amount of carbon in fly ash was predicted to increase with an increase of biomass shares in co-firing, due to the presence of relatively large biomass particles which would lower the overall efficiency.

Another issue in multi-phase particle-gas flows is that particles tend to locally accumulate in turbulent flows associated with the eddy motions. This phenomenon of preferential concentration in certain areas is also called inertial clustering and has been observed by several researchers (Fessler et al., 1994; Longmire and Eaton, 1992; Wood et al., 2005). The preferential particle concentration causes inhomogeneities in the concentration field and can affect the ignition and combustion behavior of particles (Ryan and Annamalai, 1991; Zhao et al., 2007), pyrolysis and reaction rates (Russo et al., 2014) and soot formation (Göktepe et al., 2016).

As discussed above, the aerodynamic properties of biomass particles can greatly influence the efficiency of the firing system and there is still a lack of understanding the behavior of biomass particles in turbulent swirling flows. The present paper addresses the effect of the swirl strength on the behavior of biomass particle motion and biomass particle dispersion characteristics in the near-field flow close to the pulverized fuel burner. Accordingly, four different swirl numbers ranging from S=0.0 to S=0.66 were investigated for the solid-gas turbulent jet at a moderate jet Reynolds number ($Re \approx 6000$). A two-phase particle image velocimetry (PIV) technique was applied to simultaneously measure particle and gas phase velocities in turbulent isothermal swirl flows (Saber, 2014). Pulverized pine particles sieved to a particle size range of 112–160 µm were used as representative of the dispersed phase. The gas velocity was measured both in the presence and the absence of particles in order to assess the coupling of particle and gas phases. Moreover, the particle velocity field was extracted by employing a particle tracking algorithm to raw particle images.

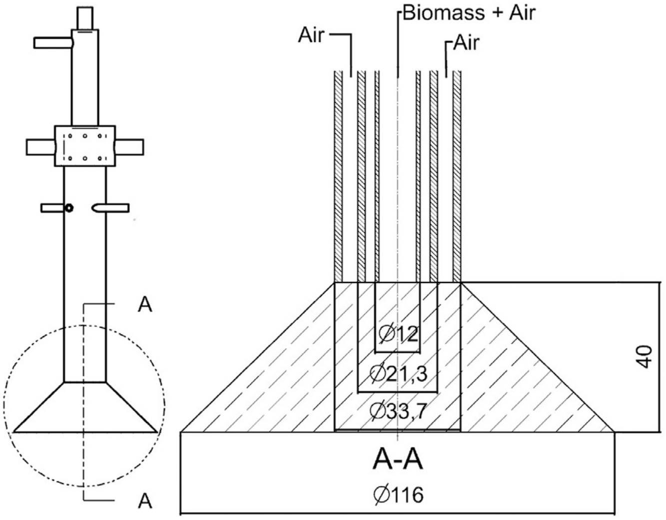


Fig. 1. Schematic diagram and cross section of the swirl burner used in this study. Note that units are given in mm.

2. Experimental setup

2.1. Laboratory-scale pulverized wood swirl burner

The swirl burner was dimensioned for a maximum output power of 30 kW and consists of three concentric tubes, two for primary and secondary air streams and one for flammable gases, e.g. methane, in order to support the flame during start-up (see, Fig. 1). The primary air stream is supplied to a 12 mm diameter central tube together with pulverized biomass particles. The secondary air stream is split into two branches named as an axial air stream and a tangential air stream. The axial air stream enters the outermost tube, flowing sequentially through two 12 mm diameter tubes, an annular settling chamber and twelve 2 mm diameter injectors intended to give a uniform distribution of the air into the outer annulus. The aim of the annular settling chamber is to reduce the flow fluctuations. The tangential air stream is mixed with the axial air stream through four 6 mm diameter tubes that are aligned in a tangential direction with respect to the centerline of the burner geometry. The burner design makes it possible to adjust the ratio between axial and tangential mass flow rates and to obtain a wide range of swirl numbers without changing the total mass flow rate. In this study, the swirl number was determined from the ratio of the tangential to the axial momentum estimated from the burner geometry (Claypole and Syred, 1981). Although it does not truly represent the real swirl number, it makes it possible to compare different cases. In the present study, no flammable gas was used, therefore there was no flow through the innermost tube. Based on visual observations, the swirl flow is rotated around the geometric center in an anti-clockwise direction. The swirl burner is surrounded by a plexi-glass conical section (denoted in the rest of the paper as "quarl"), which slows down the velocity of the annular jet flow by gradually increasing the flow area. The quarl