Microwave Doppler flow sensor for chemical looping combustion systems

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***Abstract*—We report on the development of a microwave Doppler sensor designed for the measurement of mass flow rates of oxygen carrier particles in a chemical looping combustion system. The high temperature and pressure in the combustion system imposes difficult constraints on the sensor design. We describe a recently developed microwave launcher and report recent room-temperature testing of the microwave electronics. A novel approach for real-time analysis of the sensor output is described and demonstrated. We will show independent extraction of the stream velocity and the mass density.**

I. Introduction

Chemical looping combustion systems [1] have an exhaust consisting almost entirely of carbon dioxide and water vapor. After condensation of the water vapor the carbon dioxide can be utilized or stored without the need for an expensive separation process, making chemical looping combustion potentially more cost and energy efficient than a conventional boiler with carbon dioxide separation added to the exhaust cleanup. The NETL-RUA is performing research and development to improve the technology readiness level of chemical looping combustion technology through the Industrial Carbon Management Initiative (ICMI).

Figure 1 shows an experimental chemical looping reactor system presently at NETL. Oxygen carrier particles (typically a metal oxide) are oxidized in the air reactor and are transported to the fuel reactor. In the fuel reactor, the particles are reduced in reactions with the fuel, and then returned to the air reactor. The circulation rate [mass/ unit time] is a key process parameter. Measurement of the circulation rate is challenging because the system is pressurized and is operated at high temperature (~ 1000 °C). We are developing a microwave Doppler sensor to measure the particle velocity and the particle density independently. The sensor is to be located at the upper crossover in Figure 1.

In this paper we report on the design of the microwave Doppler system including a microwave launcher suitable for integration into the chemical looping system. We describe a novel approach to signal processing required to extract particle density and particle velocity from the microwave Doppler signal. Finally, experimental results obtained in room temperature testing will be presented.

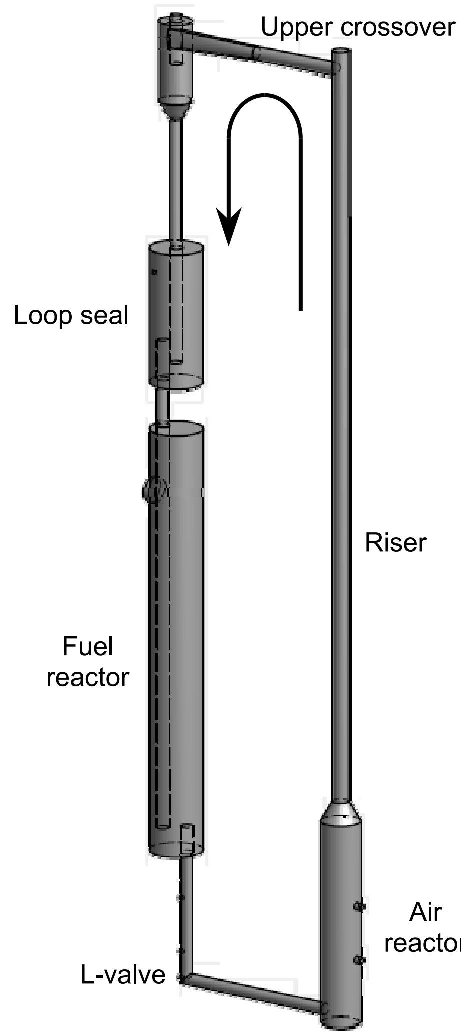

Figure 1. Chemical looping reactor at NETL. The Doppler sensor is located in the upper crossover. The arrow shows the direction of particle circulation. The thermal insulation and outer housing is not shown.

II. MICROWAVE LAUNCHER

Figure 2 shows a block diagram of the microwave electronics used in these experiments. The signal from a local oscillator at frequency f_0 passes through a circulator and is emitted from an antenna. The reflected wave is mixed with the local oscillator signal and then low-pass filtered. The resulting low-frequency signal is digitized by a data acquisition system for processing as discussed below.

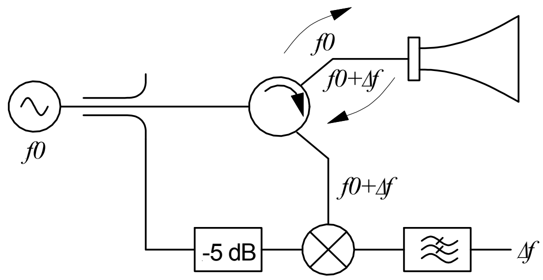

Figure 2. Block diagram of the microwave electronics.

The reflected wave from an object moving at velocity v interacting with a microwave beam at frequency f is shifted by

$$\Delta f = 2f\frac{v}{c}\cos\theta \tag{1}$$

where θ is the angle between the direction of propagation of the beam and the object velocity vector and c is the velocity of light. For microwave frequencies of 10 GHz and velocities of the order of a few meters/ sec the the frequency shift is a few hundred Hz. The angle θ is typically near 45 degrees as a large frequency shift is desired but small angles are geometrically impractical. The power reflected from the particles is approximately given by

$$P_{reflected} = N\sigma_{scattering} P_{incident} \tag{2}$$

where N is the total number of particles in the beam, $P_{incident}$ the incident beam power, and $\sigma_{scattering}$ the the scattering cross section of a single particle.

The chemical looping reactor operates at high temperature (~ 1000 °C) and in addition is pressurized. The design of the microwave antenna or launcher must take these factors into account.

We have designed the launcher shown in Figure 3 for this application. An alumina cylinder acts as a waveguide. The TE_{11} mode is launched into the cylinder using a tapered plexiglas section preceded by a coaxial-to-rectangular transition. The launcher penetrates the steel housing and thermal insulation of the reactor and is oriented at an angle of 77 degrees with respect to the channel axis. Refraction at the alumina-air interface deflects the beam so that the angle between the beam and the flow velocity is near 45 degrees.

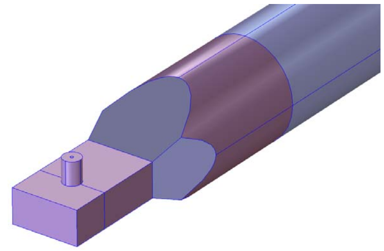

Figure 3. Microwave launcher showing transition from coaxial cable to circular waveguide.

III. DATA ACQUISITION AND ANALYSIS

The low-frequency signal from the mixer and low-pass filter is digitized at a rate of 10000 samples/ sec by a National Instruments USB-6212 data acquisition unit. This data is collected by a PC and needs to be analyzed in real time to obtain the velocity and mass density in the particle stream. As we are interested in the frequency shift it is natural to perform the Fourier transform of the acquired time-dependent data and to identify the peak frequency and amplitude. However analysis of Fourier spectrum is less straightforward for a stream of particles than for a single object.

The frequency spectra resulting from a single object and multiple particles are compared in

Figure 4.

Figure 4 shows the FFT (Fast Fourier Transform) magnitude as a function of frequency for a single ball bearing dropped 1.8 m and falling through the antenna beam. There is a single peak at 320 Hz which agrees well with the expected frequency shift expected (295 Hz).

In contrast, Figure 5 shows the frequency spectrum computed from 0.54 sec of data acquired during a flow of 150 μm ilmenite particles. The flow was provided by a table feeder and the particle fall distance was 2.1 meters. The power spectrum does not have a smooth peak although the envelope of the data is peaked near 190 Hz. This is a reasonable frequency shift as it corresponds to a velocity somewhat less than the free fall velocity but greater than the terminal velocity of a single particle. A power spectrum with rapid variations rather than a smooth envelope is not a numerical or experimental artifact; a similar spectrum arises in numerical or analytical calculations (not shown).

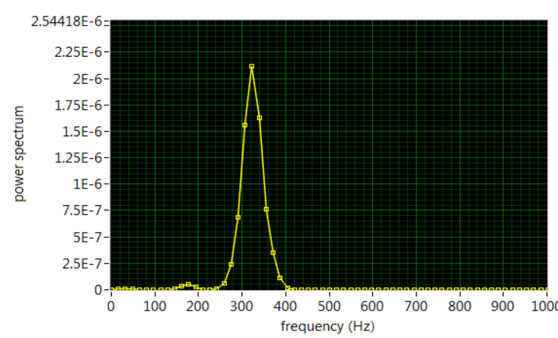

Figure 4. Frequency spectrum from a steel ball 0.157" diameter falling 1.8 m, horn angle 42 degrees; 10 GHz source.

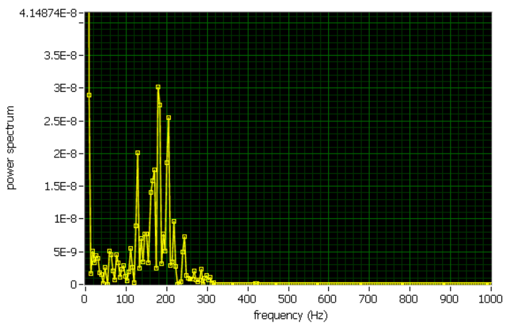

Figure 5. Frequency spectrum from 150 μm diameter ilmenite particles falling 2.1 m, horn angle 52 degrees; 10 GHz source.

In analyzing the data, it is necessary to extract the center frequency and maximum amplitude of a spectrum like that in Figure 5, with the constraint that calculations must be rapid enough to provide frequent updates (ideally more frequent that 1 update/ second) for effective process control. Early work on the application of Doppler sensing to particle flow measurements used analog signal processing [2,3] or a FFT using a minicomputer [4].

The approach we use is as follows:

- collect a chunk of data consisting of 2^n samples
- perform the FFT and compute the magnitude at each frequency
- set frequency components near less than f_{min} to zero (this reduces the impact of $1/f$ noise)
- truncate the frequency spectrum at f_{max} to exclude components that correspond to unphysically large particle velocities
- form the cumulative distribution function from the frequency spectrum
- the maximum value D_{max} of the cumulative distrubution function is a measure of the total reflected power

The parameters f_{min} (f_{max}) are set lower (higher) than the frequency range of interest. The frequency corresponding to $D_{max}/2$ is a measure of the frequency shift Δf. Figure 6 shows a typical cumulative distribution function together with the extraction of the frequency shift and D_{max}.

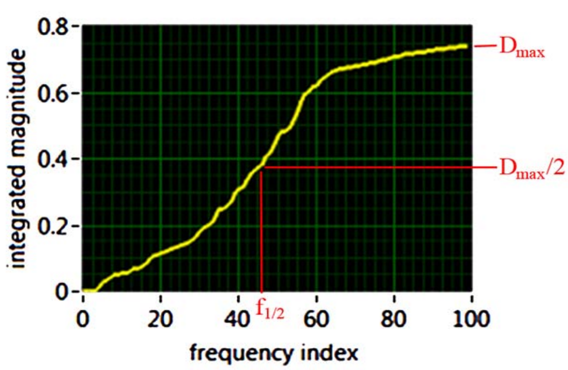

Figure 6. Cumulative distribution function showing extraction of D_{max} and $f_{1/2}$.

In the following section, we show the application of this approach to data analysis to experimental data.

IV. Application in Room Temperature Testing

The Doppler electronics and signal processing have been tested at room temperature. A continuous flow of 150 μm ilmenite ($FeTiO_3$) particles was generated using a table feeder and a drop tube. Table feeders are used to produce a controlled flow of granular substances. A table feeder consists of a speed-controlled rotary table and a scraper that scrapes particles into a funnel. A supply tube and reservoir continually replenishes the particles as the table rotates. In our experimental apparatus the funnel from the table feeder drops particles into a 5 cm inside diameter tube. The microwave antenna is located approximately 93 cm below the table feeder. The particles fall onto a scale where the accumulated mass is measured as a function of time using a modified postal balance.

Results from an experiment where the motor speed was changed partway through the flow are shown in Figure 7. In this experiment a standard microwave horn was used as the antenna and the number of samples per chunk of data was 8192. The microwave source was 10 GHz and the angle between the microwave beam and the particle flow direction was 62 degrees.

Figure 7a shows the measured mass deposited on the postal scale as a function of time. The mass flow rate is the rate of change of the total accumulated mass and is shown in Figure 7b. The step change in mass flow rate is clearly visible.

Figure 7c shows the extracted value of D_{max} as a function of time. The step change in mass flow rate is clearly reflected by a change in D_{max}. Note that a nonzero value for D_{max} is extracted before the flow of particles is started and after the supply is exhausted. This is a consequence of the noise level in the data acquisition system which gives small positive values for D_{max} even when no particles are present. Noise adds an offset to D_{max} that needs to be subtracted for accurate measurements.

Clearly it is incorrect to extract a value for the frequency shift when the frequency components are only due to noise. As a result we have introduced a threshold, slightly larger than the noise-related offset in D_{max}. When D_{max} is less than this threshold, the frequency shift is set to zero. This yields the results shown in Figure 7d, where the extracted particle velocity is plotted as a function of time. The particle velocity is nearly independent of time and corresponds, as expected, to a velocity between the free-fall velocity and the terminal velocity for a single particle.

Similar experiments have been performed using a prototype alumina launcher, although with a right-angle rather than an angled end. The flow of particles is clearly seen although noise levels so far are higher than with the horn antenna, indicating a need for improved matching.

The time required for computation is of considerable practical importance, as it is necessary to complete computation for one chunk of data while the next chunk is being collected. We have implemented the analysis using

Labview 8.6. The time required for computation is short enough even for chunk sizes as short as 256 samples even when using an ordinary laptop. For larger numbers of samples the computation time does not increase significantly and the time available for computation is greater.

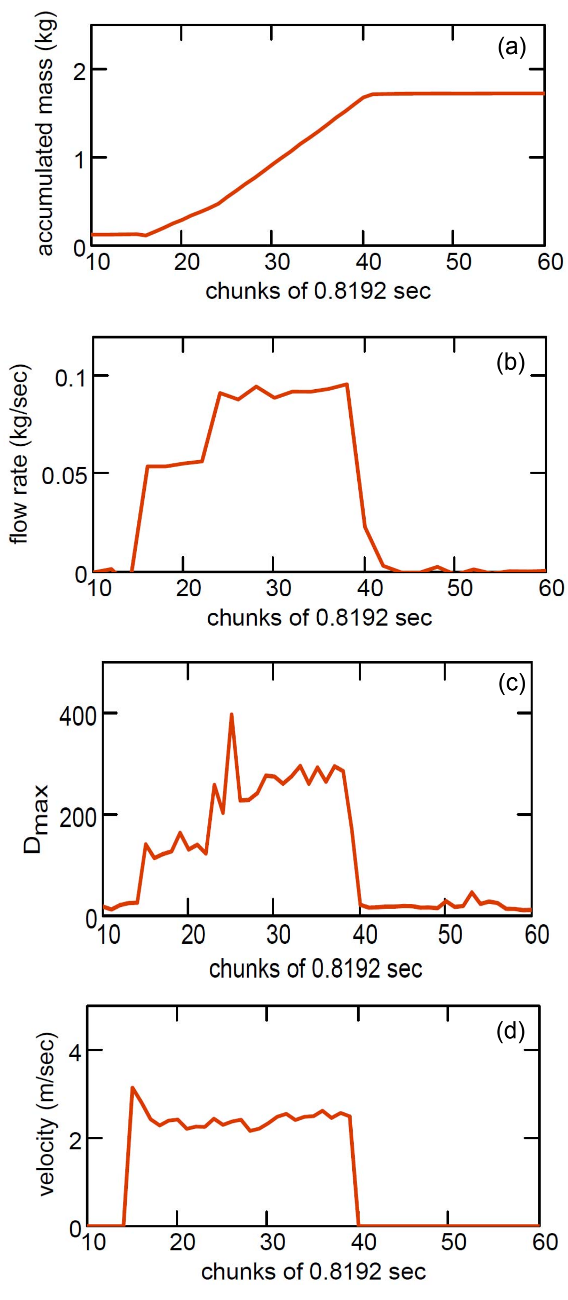

Figure 7. Data from room-temperature measurements of an ilmenite particle flow: (a) accumulated mass as a function of time; (b) mass flow rate measured using the accumulated mass; (c) extracted D_{max}, a measure of the particle density; and (d) particle velocity extracted from the measurements.

V. Conclusions

We have developed a microwave Doppler system suitable for incorporation into a chemical looping reactor. A microwave launcher has been designed that is compatible with the high temperature and pressure environment of the chemical looping reactor. A scheme for real-time data analysis has been developed to extract particle velocity and particle density information from the digitized mixer output. Operation of the system has been demonstrated in a room temperature environment. Measures of the particle density and particle velocity have been separately extracted from the data stream.

VI. Acknowledgements

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VII. References

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