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Measurement of solid mass flow rate by a non-intrusive microwave method

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ABSTRACT

The methods of accurate measurement on the real-time solid mass flow rate are very limited, especially for non-intrusive measuring approaches. This paper presents a non-intrusive measurement system on solid mass flow rate. The measuring principle is based on microwave attenuation theory and microwave Doppler Effect. A series of experiments have been carried out to test the microwave measurement method. The effects of particle properties in terms of size and relative permittivity on the measuring results have been carefully discussed. The correlations between the output signal and the solid mass flow rate have been investigated. The experiment results show that the size and material of the measured solids can significantly influence the reflected microwave signal. To improve the measurement accuracy, the correlation related on the functions of particle diameter and permittivity is proposed for the solid mass flow rate. Furthermore, the experiments under the unsteady flow condition confirm that this method is promising to be applied in the actual industrial processes.

1. Introduction

The solid mass flow rate is one of the key parameters to reveal the characteristics of the gas-solid two phase flow [1]. An accurate measurement on the real-time solid mass flow rate is important to various industry processes. The common measurement methods can be divided into two categories, the intrusive and the non-intrusive methods [2–4]. The typical examples of intrusive methods are the Coriolis methods [5] and thermal methods [6]. In actual measurement, the intrusive methods inevitably influence the solids flow behaviors, which causes the unexpected effects, e.g., affecting the flow structure and reducing the reaction efficiency. Compared with the intrusive methods, the non-intrusive ones can measure the solid mass flow rate without influencing the gas-solid behavior. Therefore, various non-intrusive methods have been developed over the last three decades [7–19]. In general, non-intrusive methods obtain the solid mass flow rate via measuring the velocity and concentration of the solids. The electrical, attenuation, magnetic resonance and tomography methods are applied for the solid concentration measurement, while Doppler, cross correlation or spatial filtering methods are used to measure the particle velocity [10–19]. However, each technique presents its own limitations under different application requirements. The complex installation and unstable operation are common disadvantages among these methods. Besides, it is also difficult to accurately measure the solid flow rate with most of the existing non-intrusive methods for the dense particle flow, which is common in industrial processes.

Microwaves with propagation characteristics have been used to measure the parameters of the solids flow. As a non-intrusive measurement method, it can obtain the solids flux data without interfering the flow. Compared with other non-intrusive methods mentioned above, the microwave indicator is relatively small in size. Thus, it is easy to install, adjust and maintain. Furthermore, the reflected signals from stationary particles do not yield Doppler Effect, and hence, the measuring errors caused by blocking can be avoided [20]. Due to these advantages, the microwave measurement method has attracted interests of many researchers [21–25]. Hrin and Tuma [23] developed a particulate loading monitor using a multimode microwave cavity. The detection of the scattered radiation by beating it with the non-scattered radiation provided an indication of the particulate loading. Penirschke and Jakoby [24–25] developed a mass flow detector using an open cylindrical resonator, and their experiment results proved that the measuring detector was comparable to commercially available mass flow sensors. However, although many researchers conclude that the microwave method has great potential to measure the solid mass flow rate, the effect of the measured particle properties (e.g., material type and particle size) on the measurement has not been well explained, which will greatly limit the application of the microwave method [26–28]. Besides, the

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Nomenclature

A	Area
c	velocity of the light in air
d	diameter
f	frequency
G	solid weight
I	current value
m	negative refractive index
P	power
Q	solid mass flow rate
R	correlation coefficient
S	power spectral density
T	time
$\overline{v}$	velocity

Greek symbols

ρ	density
θ	angle
σ	radar cross section
ε'	dielectric constant

unsteady and inhomogeneous solids flow, i.e., flow after the cyclone and long horizontal pipe with particle sedimentation, also affects the measurement of the method.

In this study, a novel system aims to measure the solid mass flow rate is developed based on the theories of microwave attenuation and Doppler Effect. An experimental system, which comprises a storage silo, a graduated butterfly valve and a vertical pipe as well as a weighing machine, is built up to test the microwave measurement method. The effects of the particle size and permittivity on the measured signals have been discussed. A correlation as the functions of particle diameter and permittivity is proposed to improve the measurement accuracy. Therefore, these results will be valuable for applying the microwave measurement method into practice.

2. Material and methods

2.1. Microwave solid mass flow rate measurement method

The solid mass flow rate in a pipe is defined as:

$$Q = \rho_a * \text{Aaera} * \overline{v} \tag{1}$$

where ρ_a is the apparent particle density in the pipe, Aaera is the cross-section area of the pipe, and $\overline{v}$ is the average particle velocity. Thus, the solid mass flow rate can be obtained by measuring the apparent particle density and velocity of particles.

The flowchart of the signal processing is shown in Fig. 1. Specifically, the microwaves with fixed-frequency (24.125 GHz) are emitted to form a microwave measuring field around the microwave sensor. With no particle in the empty pipe, the detecting microwaves will be reflected by the metal wall without attenuation. Otherwise, the microwaves will be attenuated due to the absorption and reflection of the solid particles, which makes the power of received microwave signals lower than the original emitting power. The power of the received signal is related to the concentration of solids, which can be used to estimate the average concentration of particles in the pipe. Eq. (2) [29] shows the relation between the power of signal P and power spectral density $S(f)$.

$$P = \int_{f_{\min}}^{f_{\max}} S(f)df \tag{2}$$

where $f_{\max}$ and $f_{\min}$ are the upper and lower limit of the frequency, respectively.

Meanwhile, according to the Doppler Effect, the frequency of reflected microwave is relevant to the particle velocity. The frequency shift of the Doppler signal gives direct relation to the velocity of moving object [30], which is given in Eq. (3).

$$f_d = \frac{2vf_o}{c} \cos\theta \tag{3}$$

where f_d is the frequency shift of reflected signal, v is the velocity of moving particle, f_o is the original frequency of emitting signal, c is the velocity of light in the air, and θ is the angle of arrival with respect to the incident signal.

The received Doppler signal is a superposition signal and the average frequency shift of signal f_{daver} can be calculated by Eq. (4) [29]. Therefore, the average velocity of particles can be obtained through the average frequency.

$$f_{daver} = \frac{\int_{f_{\min}}^{f_{\max}} fS(f)df}{\int_{f_{\min}}^{f_{\max}} S(f)df} \tag{4}$$

Based on the measurement of the average power and frequency of the received reflected microwaves, a voltage relating to the average velocity and the concentration of particles is generated by the microwave indicator. Then, the voltage signal is converted into a current output signal which can be collected by a data acquisition card. With proper

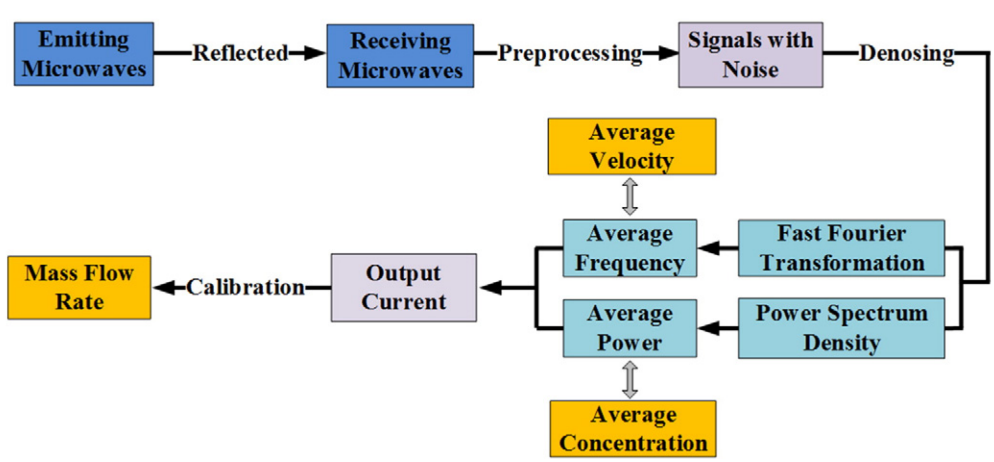

Fig. 1. Flowchart for the microwave measurement of solid mass flow rate.