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Powder conglutination detection in polypropylene production pipelines using acoustic-ultrasonic technique

Hongwei Hu *, Chengbao Ye, Xianghong Wang, Jie Zhang

College of Automotive and Mechanical Engineering, Changsha University of Science and Technology, Changsha 410114, PR China

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ABSTRACT

In the production of polypropylene, powder conglutination in pipelines easily leads to blockage, which can seriously affect the operation safety of the pipeline, so it is very important to detect and quantitatively evaluate the powder conglutination. This paper proposed an acoustic-ultrasonic (AU) quantitative evaluation method for powder conglutination detection in polypropylene production pipelines. A simulation model was developed to investigate the wave propagation characteristics of conglutinated layers with different areas and thicknesses using stress wave factors (SWF). Experiments were then conducted to develop a quantitative evaluation method for polypropylene powder conglutination. The results show that the relative attenuation coefficients of peak amplitude, peak-to-peak amplitude and the energy and the peak of the power spectrum all follow an approximate linear relation with the areas and thicknesses of the conglutinated layers. For either area or thickness evaluation, the energy or the peak of the power spectrum of AU signals has higher sensitivity than peak amplitude or peak-to-peak amplitude. Moreover, compared with conglutinated area evaluation, all the SWF models for thickness evaluation were more reliable, where the errors were all less than 7%. As a result, the AU technique is an effective means to detect powder conglutination in polypropylene production pipelines, and high sensitive and accurate quantitative evaluation is feasible with some of the stress wave factors of AU signals.

1. Introduction

Polypropylene has the advantages of low density, good processability, favourable heat resistance, and being non-toxic and tasteless; it is widely used in automobiles, household appliances and many plastic products. In the process of the polypropylene production using gas phase method, the polymer particles will easily condense and adhere to the inner wall of the loop reactor during the gas phase polymerization. In addition, the spherical polymer particles are generally transported by pipelines, the powder particles will inevitably adhere to the inner wall of the pipeline due to its poor transportation, static electricity and the low heat exchange capacity [1], which results in a conglutinated layer for blockage in a pipeline or even an explosion accident [2]. Therefore, it is necessary to detect polypropylene powder conglutination during its production and pipeline transportation.

There are already several ways to detect powder conglutination and blockage, including the stress–strain method, γ-ray diffraction method, and transient-based method. Rogers et al. [3] located blockage in pipelines using axial strain sensing elements and strain gauges, and found that it was possible to define the minimum and maximum ranges of a blockage by calculating the changes of stress and strain in the inner wall of the pipeline, but this method needs multiple point-defect to ensure accuracy. Alipour et al. [4] found that the γ-ray diffraction method could determine the type and size of the blockage in fire-protection piping systems by calculating the γ-ray photons. But γ-rays are easily affected by air humidity and particulate matter inside the pipe. Moreover, they are not suitable for long-distance pipeline inspection. Meniconi et al. [5] and Duan et al. [6] judged pipeline blockages using a transient-based method, where a transient pressure wave was injected into the conduit and the response was measured at specified locations. Then the location and size of the blockage were obtained by shifts of resonant frequencies and variation of the wave phase and amplitude. But the temperature has a great influence on the propagation velocity of transient pressure wave and it is also not suitable for the long-distance pipeline inspection.

Acoustic detection is an effective method to detect pipeline blockages or powder conglutination. Pulse-echo ultrasonic testing can detect the location of a pipeline blockage by time-of-flight. Papadopoulou et al. [7] and Duan et al. [8] obtained the resonant by calculating the phase difference of echo signals and transmitted signals in pipelines, which could reflect information about the length and area ratio of the conglutinated layer. But this requires multiple measurements with ultrasonic waves of different frequencies and different propagation distances to get a sufficiently accurate phase difference, so this method has disadvantages in terms of efficiency and real-time performance. Its detection results are also

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[*] Corresponding author.
E-mail address: hhwlucky@163.com (H. Hu).

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easily affected by pipeline structures and reflective media. Rice et al. [9] measured the acoustic attenuation and backscattering coefficients of the acoustic signal propagating through the suspended particles in the pipeline using dual-frequency inversion method, and the backscattering coefficients were used to successfully determine the concentration profile in suspensions of solid particles in a carrier fluid. Similarly, Furlan et al. [10] used A-scan ultrasound technique for measuring local particle concentration in slurry flows. These methods are effective in fluid where the backscattering and attenuation of the ultrasonic waves are relatively easy to detect, while they are not suitable for polypropylene powder conglutination because of lacking fluid as coupling media. Ma et al. [11] monitored the thickness of the epoxy layer using the cutoff frequencies of the torsional modes of the ultrasonic guided waves, but this method requires accurate acquisition of the complex dispersion and multi-mode characteristics of the ultrasonic signals in pipelines. Hii et al. [12] effectively monitored the flow characteristics of solid particles in pipelines by acoustic emission (AE) testing. Sheahan et al. [13] also use AE to monitor the pellet coat thickness reliably. However, AE is a passive technique and is not suitable for the detection of static powder conglutination.

The acoustic-ultrasonic (AU) technique is known as “acoustic emission simulation with ultrasonic sources” [14], where the ultrasonic sources are excited to generate stress waves in the surfaces and interior of components. The response waves will be received by receiving transducers, and then the material properties can be evaluated by analysis of the received signals, so it is an active non-destructive testing method to evaluate material properties. Compared with other methods, the AU technique is less sensitive to the structure of measured components and does not need to load the components. Besides, AU testing is highly efficient and enables the quantitative evaluation of the component properties by the stress wave factors (SWF) of the AU signals. The AU testing method has been successfully applied to a variety of applications such as pipeline corrosion inspection [15], fatigue crack monitoring [16–17], damage classification of aerospace structures [18], but so far it has not been used to powder conglutination detection.

In this paper, the AU technique was used to detect powder conglutination in a polypropylene production pipeline, and the method for quantitative evaluation of the conglutinated powder layer is discussed. Firstly, the SWF of AU is introduced. Secondly, the simulation model is built to investigate the attenuation characteristics of the AU signals and SWF versus the conglutinated layer with different areas and thicknesses. Finally, the AU testing system is built to detect powder conglutination in a pipeline, several powder conglutinated layers are made for experiments, and the quantitative evaluation method for the areas and thicknesses of the conglutinated powder layers is discussed.

2. The SWF of AU

The AU technique uses the relative efficiency of stress wave propagation to characterize the properties of the measured components, and the SWF is usually used as the evaluation indicator. The SWF generally includes the amplitude, energy and power spectral density of receiving signals in the time domain and frequency domain [19]. The SWF employed in this paper includes peak amplitude, peak-to-peak amplitude, energy and the peak of the power spectrum, the average relative attenuation coefficients of which are expressed as follows:

$$\overline{S_{\mathrm{V}}} = \frac{1}{N}\sum_{i=1}^{N} 20\,\log\frac{V_{\max}}{V_{\max 0}} \tag{1}$$

$$\overline{S_{\mathrm{P}}} = \frac{1}{N}\sum_{i=1}^{N} 20\,\log\frac{(V_{\max}-V_{\min})}{(V_{\max 0}-V_{\min 0})} \tag{2}$$

$$\overline{S_{\mathrm{E}}} = \frac{1}{N}\sum_{i=1}^{N} 20\,\log\frac{\int_{t_1}^{t_2} V^2 \mathrm{d}t}{\int_{t_1}^{t_2} V_0^2 \mathrm{d}t} \tag{3}$$

$$\overline{S_{\mathrm{F}}} = \frac{1}{N}\sum_{i=1}^{N} 20\,\log\frac{\int_{f_1}^{f_2} S^2 \mathrm{d}f}{\int_{f_1}^{f_2} {S_0}^2 \mathrm{d}f} \tag{4}$$

In the above equations, $\overline{S_{\mathrm{V}}}$ and $\overline{S_{\mathrm{p}}}$ are the relative attenuation rates of peak amplitude and peak-to- peak amplitude respectively, $V_{\max 0}$ and $V_{\min 0}$ are the peak voltage and trough voltage of the receiving signals respectively without conglutinated powder layers in the pipeline, $V_{\max}$ and $V_{\min}$ are the peak voltage and the trough voltage of the receiving signals with conglutinated powder layers in the pipeline respectively, N is the number of samples in each signal, $\overline{S_{\mathrm{E}}}$ is the relative attenuation rate of the signal energy, t_1 and t_2 are the time intervals, and V and V_0 are the receiving signal voltages with and without conglutinated powder layers in the pipeline respectively. $\overline{S_{\mathrm{F}}}$ is the relative attenuation rate of the peak of the power spectrum, f_1 and f_2 are the frequency intervals, S and S_0 are the frequency functions with and without conglutinated powder layers in the pipeline respectively.

3. Simulation analysis

The stress wave in a solid during AU testing is essentially a kind of visco-elastic wave, which obeys the wave motion equation given as follows [20]:

$$\rho\frac{\partial^2 \boldsymbol{w}}{\partial^2 t} = \left[\mu+\eta\frac{\partial}{\partial t}\right]\nabla^2\boldsymbol{w} + \left[\lambda+\mu+\phi\frac{\partial}{\partial t}+\frac{\eta}{3}\frac{\partial}{\partial t}\right]\nabla(\nabla\bullet\boldsymbol{w}) \tag{5}$$

where ρ is the material density, λ is the first Lamé constant, μ is the second Lamé constant, η is the shear viscosity, ϕ is the bulk viscosity, ∇ is the gradient operator, $\nabla\bullet$ is the divergence operator and $\boldsymbol{w}(\mathrm{x},\mathrm{y},\mathrm{z},\mathrm{t})$ is a three-dimensional column vector whose components are the x, y and z components of displacement of the medium at location (x, y, z).

According to the wave motion equation and the theories about transmission, reflection and refraction of wave propagation in different mediums [20], an acoustic model for an AU stress wave propagating in the pipeline and the conglutinated powder layer can be developed. The numerical solution can be obtained by the finite difference time domain (FDTD) method. In this paper, the simulation model for the inspection of powder conglutination in pipeline was established by Wave3000™ [21], which is a numerical simulation software to compute ultrasonic wave propagation using FDTD. The three-dimensional view, the two-dimensional cross-sectional view and the two-dimensional snapshot of the sound field of the simulation model are shown in Fig. 1. This model is composed of the pipeline, polypropylene conglutinated layer, transmitting and receiving piezoelectric transducers, and air outside the pipeline. The pipeline is made of stainless steel, 120 mm long, inner diameter of 30 mm, wall thickness of 5 mm, density of 7800 kg/m^3, with the longitudinal wave and shear wave velocity of 5900 m/s and 3200 m/s respectively. The conglutinated layer is made of polypropylene, density of 880 kg/m^3, with the longitudinal wave and shear wave velocity of 2340 m/s and 820 m/s respectively. The other parameters in Eq. (5) are set by default. The piezoelectric material of the transmitting and receiving transducers is PZT-5H, both transducers have a diameter of 3 mm, and they are symmetrically placed on the pipeline at 50 mm distance from the centre of the pipeline. The transmission source signal is stimulated with a sine wave with a frequency of 150 kHz and duration of 30 μs. The right and left sides of the pipeline and the boundary of the conglutinated layer and pipeline are with a low-reflecting boundary condition [22], so that the echo signals reflected from both sides and the boundary of the conglutinated layer and pipeline will not be considered.