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Pressure loss reduction in horizontal plug conveying of granular particles with ultrasonic vibration

Kenji Kofu

Department of Mechanical Engineering, College of Science and Technology, Nihon University, 1-8-14 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan

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ABSTRACT

Ultrasonic vibration was applied to the horizontal plug conveying of granular particles, and the pressure drop was measured. As shown by the results of this experimental research, the pressure loss decreased linearly with increasing ultrasonic vibration regardless of the type of particles and the flow conditions. Therefore, ultrasonic vibration can be used to reduce the frictional resistance between packed particles and the wall surface of a pipe. Additionally, it was shown that this reduction depends on particle velocity. In this study, pressure sensor sheets were attached inside the pipe wall at every 45°, and the wall pressure was measured while a plug passed through. If the particle velocity increases, the particles are pushed strongly, spread widely, and the pressure of the particle bed against the pipe wall increases. Eventually, it becomes difficult to float particles and many particles make contact with the pipe surface. Therefore, a large ultrasonic effect cannot be expected under high-velocity conditions. However, this ultrasonic vibration is effective to prevent choking because the pressure loss can be reduced drastically when the particle velocity is slow.

1. Introduction

Pneumatic conveying [1,2], which is one form of particulate conveyance, has many advantages over the container method, belt conveyor, and other types of mechanical methods. The advantages include high speed, large amounts of particle transportation, sanitary conditions, flexibility of routing pipe, low maintenance cost, factory automation and inexpensive processing. Pneumatic conveying can be broadly characterized as either dilute-phase high-velocity flow and dense-phase low-velocity flow [3]. One of the dense-phase low-velocity methods, called plug conveying, is often adopted for the prevention of pipe wall wear and particle attrition, as well as energy saving [4]. Plug conveyance is attracting many researchers and several reports have been published, including those on flow visualization [5–7], pressure loss [8–12], friction [13–16], and simulation [17–20].

However, the plug conveying system has a disadvantage when the conveyance power becomes large. It was found that frictional resistance is important for forming the particle bed in this system [18,21]. Additionally, many researchers consider the only wall friction when they derive the pressure loss equation [8–12]. This means that the major cause of pressure loss can be assumed to be frictional resistance between the packed beds and the wall surface. As one of the methods to eliminate pressure loss, Kano [22] proposed to apply mechanical vibration in pipelines. However, this proposal has some problems, e.g., a large reduction in friction cannot be expected because the vibration frequency is low, the required operating power of the equipment is high, and the device is complex. Therefore, this method has not been utilized. Mracek [23] applied ultrasonic vibration with a progressive wave for conveying particles in a pipeline. This method does not use air flow and a large amount of particles cannot be conveyed. Additionally, particles cannot be conveyed over a long distance because the progressive wave is easily reduced. Li proposed the application of a swirl for pneumatic conveying [24] and claimed that the pressure loss is smaller than that under no-swirl conditions in a low-velocity region. But this method is difficult to employ for dense-phase flow because the swirl easily shrinks along the flow direction.

Therefore, we propose the application of ultrasonic for horizontal plug conveying. Ultrasonic waves have been recently applied in various fields such as machining, electronics, chemical processing, and the food industry. Consequently, research on ultrasonics has been widely carried out, with applications including searches for sunken undersea objects [25], decontamination of hazardous chemicals [26], effects in cancer cells [27,28], and piping inspection in food factories [29]. Some researchers have already reported that ultrasonics can float heavy material and reduce the frictional resistance against the wall of a pipe [30–32]. Our group confirmed that ultrasonics can be used to reduce the frictional resistance of static particles on a flat plate [33]. It has also been shown that ultrasonics has the effect of decreased frictional resistance regardless of the type of particles. The particle properties that have an effect on friction reduction are the acoustic transmission coefficient and bulk density. In contrast, the particle shape and particle diameter have little effect on the reduction of friction. In this method, the ultrasonic device is simple and cheap, generation power is low, and a large reduction in

E-mail address: kofu@mech.cst.nihon-u.ac.jp.

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pressure loss can be expected if the ultrasonic vibration is applied to horizontal plug conveying.

The purpose of this study was to investigate the reduction in pressure loss in horizontal plug conveyance via ultrasonic vibration while varying the type of conveyed particle, the flow velocity, and the pipe diameter. Additionally the wall pressure was measured and the relationship between the reduction in pressure loss and the wall pressure was investigated experimentally.

2. Experimental devices and method

The experimental ultrasonic devices are the oscillator, amplifier, and bolt-clamped Langevin type transducer, which are connected as shown in Fig. 1. The voltage frequency generated by the oscillator is $f =$ 20.5 kHz because this was the resonance frequency of the piezoelectric device in the bolt-clamped Langevin-type transducer. This voltage was amplified 55 dB by the amplifier, then input into the piezoelectric device and amplified by the exponential horn. A resonance rod was used to connect the horn and vibration pipe, and to transmit the maximum vibration to the pipe. The material of vibration pipe is duralumin, and this pipe was designed to resonate at 20.5 kHz as in the piezoelectric ceramic device. An inside diameter D of 40, 50 or 60 mm was used for the vibration pipe, and the length in the longitudinal direction was 200 mm. The vibration mode of the pipe was designed to have eight antinodes, as shown in Fig. 2, when the 20.5 kHz frequency voltage was applied. The vibration velocity v_A at the pipe surface was measured with a laser Doppler vibrometer, and the amplitude A_m is obtained from Eq. (1).

$$A_m = \frac{v_A}{2\pi f}. \quad (1)$$

The amplitude was measured every 5 degrees in the circumferential direction except ±20 degrees at the bottom because the device stand blocks the laser beam. In this paper, the angle in the circumferential direction is expressed as θ, and top surface in vertical direction is defined as $\theta = 0°$. Therefore resonance rod exists at $\theta = 180°$. The amplitude was also measured every 5 mm in the longitudinal directions.

The oscillator generated 50 mm voltage regulator modules (VRMs), which were input into the bolt-clamped Langevin-type transducer. Then, the flexural vibration generated at each pipe and the amplitude at each position was measured with the laser Doppler vibrometer. Additionally, the laser was fixed at some position on the top surface of the vibration pipe, the input voltage was increased gradually, and A_m was measured. The relationship between the input voltage and A_m was then investigated.

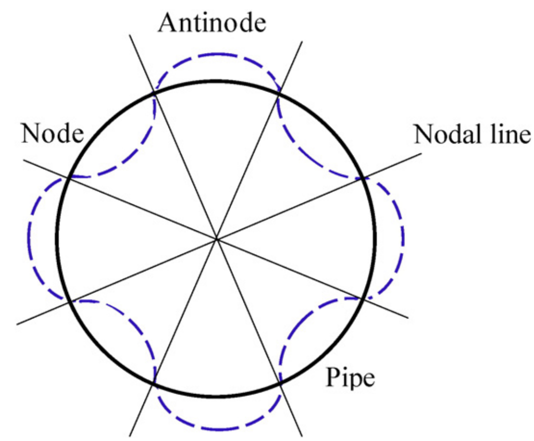

Fig. 2. Vibration mode with 8 antinodes.

The experimental devices for plug conveying are shown in Fig. 3. In this experiment, a compressor was positioned at the initial point and a positive pressure system was employed. The air chamber was used to accumulate the compressed air. In order to decompress the compressed air, a regulator was attached behind the air chamber. To measure the air mass flow rate, a flow meter was installed after the regulator. The particle supply valve was attached to the outlet of the blow tank and the particle mass flow rate was controlled. This flow rate was measured by the load cell, which was attached to the blow tank. The pipe line was made of acrylic and the entire length was approximately 13 m; an inner diameter of 40, 50, or 60 mm was used, as with the vibration pipe. The vibration pipe was installed in the horizontal pipeline. To measure pressure loss in the plug while passing through the vibration pipe, two pressure taps were attached at both ends of the vibration pipe. The taps were connected to the digital recorder through a dynamic strain gauge. Then, the value of the pressure was captured every 0.05 s, and the reduction in the pressure loss in the vibration pipe due to ultrasonic vibration was analyzed. While each plug passed through the vibration pipe, the pressure at each sensor was taken. The pressures of 20 plugs were taken and the pressure difference between these sensors was calculated. The average value of $\Delta P/L_P$ was considered to be the pressure loss in a plug.

Photoelectric sensors were used to obtain the plug velocity W_P. A pair of photoelectric sensors was positioned at both sides of the pipe line. A sensor transmits the laser beam, and this can pass through the pipe cross section if particles do not exit and block. Eventually the other sensor can get this laser beam; however, the receiver cannot

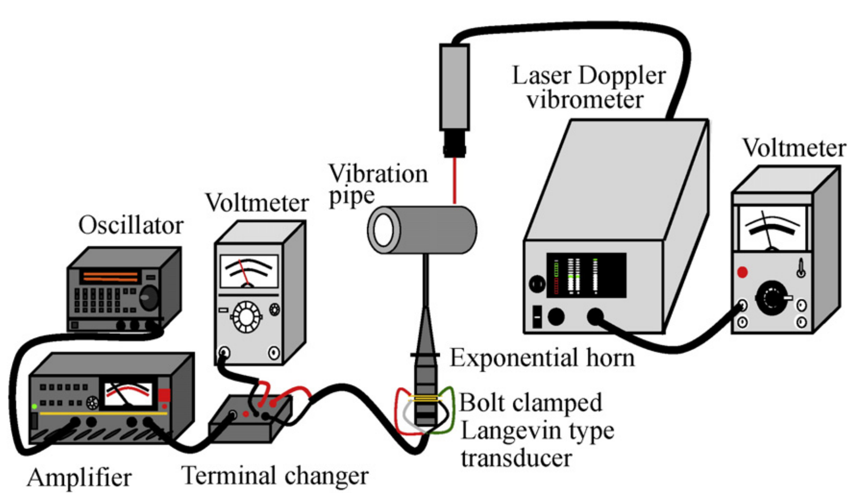

Fig. 1. Ultrasonic generation apparatus.