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Oil mist transport process in a long pipeline on turbulent flow transition region

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ABSTRACT

Internal gas velocity fluctuations and their effects on the mist diffusion process were examined in a long horizontal pipe to understand oil mist transportation, particularly in the laminar-to-turbulent flow transition region. Three hot-wire anemometers and aerosol concentration monitors were used to deduce these effects as the two-phase mist flow gradually developed in the stream-wise direction. We found significant axial mist diffusion at Reynolds numbers (Re) < 1000 because of passive scalar transport by Poiseuille flow. However, this diffusion was restricted by the non-zero inertia of the mist at a Stokes number, $O(10^{-5})$, relying on the Brownian motion of the mist. At $Re > 2400$, a sharp mist waveform was maintained by a turbulent flow with active radial mixing. New data were obtained within the range of $1000 < Re < 2400$, which cannot be explained by interpolation between the above-mentioned two states. The mist concentration displays multiple temporal peaks at $Re < 2000$ owing to perturbations of localized turbulence as well as radial anisotropy as being conveyed more than 2000-diameters in distance. This behavior is caused by intermittent disturbances induced by the pipe wall roughness, which sharply distorts the wall-aligned laminar mist layer left by parabolic axial stretching of local laminar flow.
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1. Introduction

The contamination of an industrial gas transport pipeline with an oil mist can lead to a range of problems. For this reason, oil mists must be purged using a clean gas and then removed by some means, such as by filtration. It is therefore important to obtain an understanding of the changes in the mist concentration within a pipeline while purging. The flow field inside pipes during the ordinary transport of a natural gas is generally turbulent. However, the flow velocities are lower than usual when conducting a purge operation since temporary interruption of the gas supply is required. This means that the mist diffusion phenomena that occur during both laminar, transitional, and turbulent flows must be clarified.

The diffusion behavior subject to turbulent flow can be classified according to the associated Stokes number (St) of the mist. For $St \ll 1$, individual mist particles are passively transported by turbulent eddies, and the resulting diffusion is dominated by the turbulent mixing properties (Flint and Eisenklam, 1969; Ekambara and Joshi, 2003; Takeuchi and Murai, 2010). This turbulent diffusion also promotes the deposition of mist on the internal walls of the pipeline. So, the axial transport of the mist can be described by a combination of turbulent diffusion and the associated pipe-wall deposition rate. In this case, the mist concentration can be approximated as a symmetric Gaussian profile in the pipe axial direction, and therefore the time required for the mist purging is easily modeled by a one-dimensional advection-diffusion equation (Fick's law).

In laminar flows, mist transport results from a totally different mechanism. The mist is conveyed by a parabolic velocity profile of Poiseuille flow which has a centerline velocity that is twice the cross-sectional mean velocity. This leads to a long stretched distribution of mist in the axial direction; more importantly the stretched distribution provides a sharp gradient in the pipe's radial direction. This consequently enhances the radial diffusion more than the axial diffusion. Similar cases for passive scalar or molecular transport were reported by Ekambara and Joshi (2004), and

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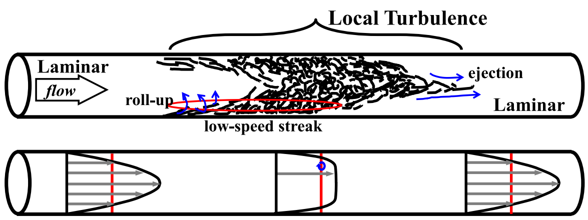

Fig. 1. Schematic representations of local turbulence.

Matas et al., (2004). The difference in behavior of the mist from the scalar or molecular scale is that mist a few micrometers in size obeys Brownian motion, associated with collisions with surrounding gas molecules (Shimada et al., 1993; Matas et al., 2004). The effective diffusion coefficient of Brownian motion is much less than that of gas diffusion, and therefore the mist is hardly diffused in the radial direction. This phenomenon could be an obstacle for an efficient purging operation in laminar flow.

Theoretical predictions of transitional flow regions remain essentially impossible; this is because of the coexistence of two different stages in laminar to turbulent flow transition. One stage involves turbulent slugs intermittently appearing in ambient laminar flow. The other stage involves the appearance of turbulent puffs with specific structures independent of the pipe wall properties. These transition processes, which occur even in single phase pipe flow, has been regarded as a fundamental topic more than a century after the initial work of Reynolds (1883). The details of these transition processes have recently attracted special interest as nonlinear dynamics of sub-critical flow transition (see, for example, Hof et al., 2004, 2006; Tasaka et al., 2010; Avila et al., 2011). We will mainly focus on the transitional regime in this paper by connecting such recent knowledge on local turbulence and dispersion dynamics in dilute mist transport.

Fig. 1 illustrates the internal structure of the local turbulence emerging between laminar flow sections in the transitional regime. The local turbulence is called a turbulent puff in the minimal case (Hof et al., 2004; Nishi et al., 2008; Shimazu and Kida, 2009) while it is called a turbulent slug in longer cases. The authors' group also succeeded in visualizing the turbulent puff to reveal the three-dimensional vortical structures within (Ohkubo et al., 2016). Inside the local turbulence, low-speed streaks and stream-wise vortex structures are present in proximity to the wall, where frictional stress increases locally. These structures are elongated downstream owing to high speed flow in the pipe center of the neighboring Poiseuille flow, forming a blunt boundary between the laminar and the turbulent regions. In industrial pipelines, multiple occurrences of such local turbulence should be considered as they are typically longer than 1000 times the pipe diameter. At relatively large Reynolds numbers within the transition region, the overall pipeline is considered as a spatially intermittent distribution of laminar flow and turbulent slugs. This enables us to estimate the overall pressure loss (Moody, 1944) and mass diffusion coefficient (Flint and Eisenklam, 1969; Ekambara and Joshi, 2003) by finding the value between that for laminar and turbulent flows. In contrast, a specific turbulent puff structure occurs at lower Reynolds numbers, which does not give a valid estimation by taking intermediate values. A puff can be understood as the minimal elementary turbulence sustainable in the pipe flow. It propagates along the axial direction with a specific lifetime (Hof et al., 2003, 2006; Peixinho and Mullin, 2006; Tasaka et al., 2010). The sustainability of a puff indicates independence on the pipe wall properties; the structure will persist downstream even inside a completely smooth pipe. This phenomenon can therefore be distinguished from a turbulent slug.

Based on the above, the behavior of a mist in transitional regions can be predicted by several aspects as follows. First, mist diffusion will result from vortices that develop inside local turbulence. Second, the mist suspended in the local laminar flows will be conveyed along the center of the pipe faster than the cross-sectional mean velocity, and will eventually reach the backside of slowly migrating local turbulence so as to diffuse inside the turbulence (see the lower illustration in Fig. 1). Last, rapid forward acceleration will occur in the center of the pipe at the forward side of the local turbulence because of connection to a re-laminarized velocity profile. The mist ejected from the local turbulence will subsequently experience only minimal diffusion inside the laminar domain and will migrate rapidly to reach the next downstream local turbulence. This peculiar mist behavior will lead to a complex diffusion process that cannot be explained by a state intermediate between fully laminar and fully turbulent flows.

In this context, the present study was designed to address two topics. One of these is related to the industrial objectives noted above; that is, the optimization of mist purging operations. The other is the investigation of the fluid dynamics during flow transitions that affect the mist behavior. In particular, the pipe flows employed in natural gas pipelines vary from those used in the idealized experimental work referenced earlier. In-house experimentation uses smooth wall surfaces and short test lengths. In contrast, the internal surfaces of industrial pipelines often exhibit significant roughness owing to absorbed solid-state scales and gaps at pipe joints. This roughness disturbs the flow field in proximity to the wall, triggering local turbulence in the transition region. In pipes shorter than 50 times their diameter in length, this effect is rarely observed because either the laminar or turbulent state occupies the length of the pipe. For this reason, in the present study, we studied unique phenomena that becomes observable only in long pipeline systems, with lengths over 2000 times their diameters.

This paper begins by explaining the apparatus and measurement instruments associated with our experimental pipeline. Prior to mist injection, we measured the velocity fluctuations during the flow of clean nitrogen gas inside the pipe, using hot-wire anemometers (HWAs), so as to understand the substantial flow transition processes that take place in a very long pipe. The latter half of the paper reports the manner of the mist diffusion measured at far downstream locations, at which streamwise history of the gas phase inside the pipe affects the mist concentration characteristics especially in the earlier stages of the flow transition.

2. Measurements of internal local turbulence in a pipe

2.1. Experimental facility

A schematic of the 1:1 scale test pipeline facility used to simulate a natural gas pipeline is shown in Fig. 2, while Fig. 3 presents a photograph of the overall facility. The straight test pipe section consists of multiple steel pipe sections with an inner diameter, D, of 81.0 mm. The total length of the pipe, L, is 163.3 m, such that L/D is 2016. The pipe sections are connected by welds at intervals of approximately 5 m, and the associated welding back-bead height is approximately 1 mm. The internal wall surface roughness of each pipe is approximately 10 µm. Compressed nitrogen with no humidity was used as the test fluid, and the pressure in the pipe was adjusted to 6 kPa (gauge) with a pressure regulator at the most upstream position. Various flow rates were examined and set using a flow control valve installed at the most downstream position. The pipe wall temperature was kept steady within +3°C of the gas temperature during the trials. Two HWA probes were installed at positions, x, of 5.9 m (upstream) and 158.1 m (downstream) or 5.9 m (upstream) and 82.0 m (midstream), where $x = 0$ is defined as the point of gas entry to the test pipe. All the test conditions

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