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Experimental and numerical research on the axial and radial concentration distribution feature of miscible fluid interfacial mixing process in products pipeline for industrial applications

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ABSTRACT

During the process of sequential transportation of miscible but dissimilar fluid (MBDF) in pipelines, the adjacent of different kinds of MBDF will be mixed, leading to form a section of a liquid mixed segment in the pipeline which is an important aspect of mass transfer, especially in the multiproduct pipeline. This paper represents an experimental study of sequential transportation of MBDF in a single pipeline and thereby a set of experimental loop platform for sequential transportation has been designed. Several dimensionless indices including mixed segment length, axial tailing length, and radial difference have been proposed to measure the concentration distribution in the mixed segment (CDMS) in both axial and radial directions of a pipeline. A novel numerical model to simulate the CDMS of MBDF transported in a pipeline is also proposed and solved, where the turbulence effect, the difference in physical properties of the front and tail fluid, and the adsorption effect are taken into account to investigate the diffusion coefficient and concentration distribution. The complex flow and mass transfer in transportation process can be observed in the experiment and the results illustrate that the concentration profile is asymmetrical respect to the 50% concentration point at different time and distance, which is not revealed in the solutions of existing both numerical theory and empirical formula. The simulated results figure out the radial and axial feature of CDMS and achieve a good agreement with the experimental length of the mixed segment. Thus, the tailing phenomenon is found, analyzed and simulated. Those mentioned-above 3 kinds of effects are considered to form the tailing phenomenon in CDMS interactively. The overall uncertainty of the proposed dimensionless parameters has also been analyzed. The results reveal that the length of the tail of the mixed segment (LTMS) is 22% longer than that of the front (LFMS) when taking the 5% change of concentration as the judging criteria. The detection probe located at the center of the pipe earliest detects the CDMS while the probe near the pipe wall does latest. The corresponding detection time difference is up to 25.64%. Finally, the research results can provide guidance for delivering the refined oils sequentially and cutting the mixed segment in the industrial pipelines.

1. Introduction

With the development of oil transportation pipeline, the dendritic, looped and even reticular refined oil pipeline networks have been constructed, which is characterized by multiple sources-sinks, multi-products and multi-complex branches [1–3]. There are many relatively limited kinds of oil products transported by pipelines. Different batches are transported sequentially in a long-distance pipeline and the adjacent between every two batches is characterized as mixing of miscible but dissimilar fluid (MMBDF) [4], as shown in Fig. 1(a). However, the automatic control of pipeline network, scheduling system and mixed oil control technology remain to be developed [1–5]. Furthermore, automatic scheduling of batch plans, sequential transport operation simulation, and batch interface tracking technology need to be improved. It is important to master the migration process of the mixed oil section for the preparedness of the best scheduling plan, interface tracking, operation optimization and safety assurance [6–11].

As to now, the specific revised formula adopted for calculating the length of mixed oil segment by all the major pipeline companies in the world is only applicable to their own MBDF pipelines because of the complex operating conditions, pipe parameters, and oil species. There is no widely accepted formula that can be used in all actual situations. Most of the decisive parameters in

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Nomenclature

List of symbols

A	the conductor effective area of the interface detection device, m^2
C	the local concentration of the oil, dimensionless
C_0	the volume concentration of tail oil, dimensionless
C_r	the concentration when the process of the adsorption reaches the balance, dimensionless
C_r^*	the extremity adsorption concentration, dimensionless
D_c	diffusion coefficient, m^2/s
D_{ρ_0}	the mixture coefficient of equal density oil, m^2/s
D_{μ_0}	mixture coefficient of equal viscosity oil, m^2/s
K_ρ	proportional constant, m/(Pa·s)
K_μ	proportional constant, m/(Pa·s)
K_a	the constant of adsorption, s^{-1}
K_d	stripping constant, s^{-1}
L_f	length of mixed segment front, m
L_{f05}	length of mixed segment front when taking the5% change of concentration as the judgment criteria, m
L_t	length of mixed oil tail, m
L_{t95}	length of mixed segment tail when taking the5% change of concentration as the judgment criteria, m
L^{MS}	length of the mixed segment, m
L^{DBFT}	the difference of length between front and tail of the mixed segment, m
L_D^{MS}	the dimensionless length of the mixed segment, dimensionless
L_D^{DBFT}	the dimensionless L^{DBFT}, dimensionless
Q	flow rate of the fluid, m^3/h
r	radius of the interface detection device, mm
r_0	the radius of the pipe, m
Re	Reynolds number, dimensionless
Re_j	critical Reynolds number, dimensionless
R_D^{CDMS}	the dimensionless length between front and tail of CDMS with respect to the distance between probe 1 and 4 at some concentration value, dimensionless
ΔT	the time of the mixed segment flowing through the detection device completely, s
ΔT_x^{tail}	the detecting time when average concentration is x% to 1 at mixed segment tail, s
ΔT_x^{front}	the detecting time when average concentration is 0 to x% at mixed segment front, s
ΔT_{14}^f	the difference of the time when detecting same concentration by probe 1 and 4 at mixed segment front, s
ΔT_{24}^f	the difference of the time when detecting same concentration by probe 2 and 4 at mixed segment front, s
ΔT_{14}^t	the difference of the time when detecting same concentration by probe 1 and 4 at mixed segment tail, s
u	the flow velocity at the cross section of the pipeline, m/s
v	velocity of the fluid, m/s
x	concentration value, 0–10 or 90–100, dimensionless
x	axial distance, m
ρ_c	density of mixed oil
υ	fluid motion viscosity, m^2/s
τ_0	wall shear stress, Pa
μ_c	viscosity of mixed oil, mPa·s
MBDF	miscible but dissimilar fluid
MMBDF	mixing of miscible but dissimilar fluid
IMMBDF	interface of the mixed miscible but dissimilar fluid
LTMS	the length of the tail of the mixed segment
LFMS	the length of the front of the mixed segment
CDMS	the concentration distribution in mixed segment
DBFT	the difference between the LTMS and the LFMS
LDBFT	the length of the DBFT

the formulas for calculating the length of mixed oil segment are the transportation distance, pipeline diameter and Re [12–19]. Some of the formulas have considered the characteristics of specific pipes (such as reduced diameter, the terrain structure and so on) [17–19]. But these calculated results are still different from the field data. The reason is that all the formulas are 1D (one-dimensional) empirical formula or derived from 1D analytical formula. Therefore, it is of great significance to study the process of sequentially transporting refined products in pipeline more detail. Then, the 2D or 3D (two or three-dimensional) numerical simulation methods have been taken into account to modify the above formulas [20–25]. But the 2D or 3D model is limited for industrial applications as they cannot be applied to simulate the long-distance pipelines quickly and easily, as shown in Fig. 1(a). The Fig. 1(a) shows the 3D numerical simulation of oil mixing in a horizontal pipeline, which is obtained by FLUENT software. The 3D model is selected to perform the simulation. The pipe has 1 m in length and 300 mm in diameter. With 1 m/s at the inlet, the detailed mixing process can be obtained at 0.25 s, 0.5, and 0.75 s. However, the computational time is far more than 0.75 s, which demonstrated that this 3D model cannot be used as a real-time calculation method. In order to verify the reliability of the empirical formula and validate the detailed high dimensional numerical simulation results which includes the volume concentration distribution at mixed oil interface, a series of experimental studies were carried out in the sequential transportation experimental loop platform or in industrial practical pipelines, which can also reveal the complex flow and mass transfer mechanism of different MBDF transportation process in pipeline, and reduce the deviation between the theoretical and the actual results.

Whether in the indoor experimental loop or in the industrial pipelines, some researches have been conducted on the process of refined oils transported sequentially [17,18,26–31]. These researches focused on developing an empirical correlation to calculate the mixed oil quantity which is based on the impact of flow regime, oil types, and pipeline parameters.

In 1943, Fowler and Brown [26] carried out a sequential transporting experiment with water and dilute NaCl solutions (with almost the same physical properties) in tubes of 0.124 in. and 0.313 in. as diameter and the tubes' length was from 5 ft to 105 ft. According to the MMBDF data from commercial pipelines and laboratory, the volume of the mixed segment was found to decrease with increasing Re for turbulent flow. The calculation formula of the volume of the mixed segment with minor error has been summarized.

Researchers from Shell Oil Company [27] established a fluid-scale experimental equipment to study the characteristics of mixed oil transported in pipelines. First, test pipe is installed in a room of 20 ft wide and 90 ft long with a pipeline of 0.6 in. as diameter and 5000 ft as length. A new pipeline system was built in order to better simulate the field pipeline after some trial tests [28]. The experimental flow rate was ranging from 0.44 m/s to 7.16 m/s and the Re was ranging from 500 to 195,500. More than 250 mixed oil experiments have been completed in 0.6 in. and 2 in. test pipelines. Mixed oil length calculation formula has been worked out based on mixed oil experiment results when Re is greater than 20,000.

In 1980, Zhuang [29] carried out an industrial test on the sequential transportation of gasoline-aviation kerosene in a field oil pipeline with a length of 55 km and a relatively complex terrain with a maximum height difference of 850 m and 4 pumping