EVALUATION OF MIXING LEVEL OF CONTINUOUS SINGLE PHASE PIPE FLOW USING BASIC RADIOTRACER MODELS

Evaluasi Tingkat Pencampuran Aliran Pipa Fluida Fasa Tunggal Menggunakan Model-Model Radiotracer Dasar

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ABSTRACT

Mixing phenomena, even in single phase of fluid, is still not understood well due to complicated processes including mass and momentum transfer in molecular scale. Fluid flow in axial direction always generates effect to radial flow into which inter-mixing is inevitably occured. Basic radiotracer models so called the tanks-in-series and axial dispersion models have been developed to fit the residence time distribution (RTD) curve generated from injection of isotope into a system. An experimental work has been conducted in a laboratory scale for investigating this phenomena. Small amount, around 1 x 10^{-3} liter of ^{82}Br isotope was injected instantenously into a carbon-steel pipeline of having internal pipe's diameter of 3 in (7.6 x 10^{-2} m) containing flowing water in it. Four collimated radiation detectors were placed on the pipe for recording radiation intensity from the injected isotope. The RTD curves generated from two detectors, as representative of the experiment data, each of which were placed at distance 7 and 10 m from injection point were further analysed for calculating flow parameters. The flow velocity calculated through mean residence time (MRT) was 0.13 m.s^{-1}. The tanks-in-series model gave better result than the axial-dispersion model for fitting RTD curve which representing mixing level. The best fitting of RTD curve using the tanks-in-series model is achieved when the model parameter, N, is equal to 4 approximately. High value of calculated Reynolds number in addition to the obtained value of N indicated that the mixing level of the fluid in the pipe was considerably high.

Keywords: fluid flow, single phase, radiotracer, tanks-in-series model, axial dispersion model.

ABSTRAK

Fenomena pencampuran, bahkan untuk fluida fasa tunggal sekalipun, masih belum difahami dengan baik karena proses yang kompleks yang melibatkan tranfer masa dan momentum dalam skala molekular. Aliran fluida dalam arah aksial selalu menimbulkan efek pada aliran arah radial sehingga menyebabkan terjadinya campuran antar molekul tidak dapat dihindari. Model-model radiotracer dasar yang disebut dengan model bejana berderet dan model dispersi aksial telah dikembangkan untuk mengepaskan kurva distribusi waktu tinggal (RTD - *residence distribution time*) yang dihasilkan dari injeksi isotop ke dalam sistem. Eksperimen skala laboratorium telah dilakukan untuk menyelidiki fenomema ini. Isotop ^{82}Br dalam jumlah sedikit, sekitar 1 x 10^{-3} liter telah diinjeksikan ke dalam pipa carbon-steel berdiameter dalam 3 inci (7.6 x 10^{-2} m) berisi air yang mengalir di dalamnya. Empat detektor radiasi yang terkolimasi ditempatkan pada pipa untuk merekam intensitas radiasi yang berasal dari isotop yang diinjeksikan. Kurva RTD yang dihasilkan dari dua detektor, yang mewakili data eksperimen, yang ditempatkan pada jarak 7 dan 10 m dari titik injeksi dianalisis untuk menghitung parameter aliran. Kecepatan aliran yang dihitung menggunakan waktu tinggal rata-rata (MRT – *mean residence time*) adalah sebesar 0,13 m.s^{-1}. Model bejana berderet memperlihatkan hasil yang lebih baik dibanding model dispersi aksial dalam mengepaskan kurva RTD yang menggambarkan tingkat pencampuran. Pengepasan terbaik pada kurva RTD menggunakan model bejana berderet tercapai ketika nilai parameter model, N, sama dengan 4 – hasil pendekatan. Nilai tinggi hitungan bilangan Reynold dan nilai N yang diperoleh menunjukkan bahwa tingkat pencampuran fluida di dalam pipa adalah cukup tinggi.

Kata kunci: aliran fluida, fasa tunggal, rerunut radioaktif, model bejana berderet, model dispersi aksial.

INTRODUCTION

Fluid flow is commonly encountered in industry, building and environment. However, most of the flow is multiphase as a result of mixed liquid-liquid, gas-gas and liquid-gas in any possible combinations [1,2]. Sometimes, solid phase is present in such multiphase flow [3]. Single phase flow may probably a special case because mixing is occurred among the fluid components itself of the same phase. Fluids are utilized for various useful purposes in accordance of its function. In industrial and plant installation,

fluids are mostly transmitted through cylindrical tubes infrastructure such as pipeline because high efficiency of pumping [4,5]. Flow rate, temperature, pressure and level are the most important parameters which reflect the oprating condition of fluid transportation in pipeline. Of the four major parameters, flow rate measurement may probably be the most complex system because it depends on other parameters which vary with the associated conditions [6].

Nowadays, there are many kinds of mechanical-based flowmeter sensors that have been proposed and applied in flow installations, such as electromagnetic flowmeter [7], differential pressure type flowmeter [8], ultrasonic flowmeter [9] and optical fiber optic flowmeter which provides compact in size, resistance to corrosion, multiplex capability and electromagnetic immunity [10]. Radioactrive tracer or radiotracer offer an alternative method as a tool for flow rate measuement. This method is non-invasive in providing an immediate and comprehensive picture of flow system during in operation which cannot be obtained from mchanical based flowmeter. The state of the art of the radiotracer technology for flow measurement is that it is suitable to provide on-line measurement, its high benefit to cost ratio and in certain case, radiotracer is the only technique that can be applied to harsh environment. In addition, the beauty of radiotracer method is that it can be used to calibrate the installed flow meters or to measure the flow rate in a system which is none installed flow meter. By using the radiotracer method the experimental results can be obtained immediately and experiment can be repeated many times without the need to shutdown the flow installation [11,12].

Selection of radiotracer for flow measurement is depend on physico-chemical properties of radiotracer and the traced material itself. In this sense, if the traced material is fluids the selected radiotracher should be fluids too. Injection of radiotracer into the system the radiotraer must not interact chemically with the traced material, the radiotracer must not modify the properties of the traced material and the radiotracer must not disturb the hydrodynamics of the system. Among the available tracer materials, the radiotracers of gamma emitter is probably the best choice because there are various radiotracers which have a wide range of similar physico-chemical properties with the traced material. The selected radiotracers should have high energy of gamma radiation with half-life time is comparable with the elapsed time of experiment. High specific gamma energy and small amount of injected radiotracer make it easy to be detected even in small amount without ambiguity. Because gamma energy is penetrating radiation therefore online measurement could be possible carried out [11-13]. The above mentioned selection of radiotracer criteria is also applicable for multiphase flow measurement [14-16].

Radiotracer method for flow rate measurement has been reported by several researcher previously. These scientists used radiotracer technique for various purposes, among of them are to measure vapor phase of geothermal fluids in geothermal pipeline using ^{85}Kr isotope [16]; to determine the dischareg rate of water in a canal using ^{131}I isotope [17]; to determine flow reduction based on flow change in burried pipeline of petrochemical company using ^{99m}Tc isotope [18]; to validate the pumping efficiency of the vertical turbin pumps used to pump sea water through the pipeline and also to calibrate the installed flow meter using ^{131}I isotope [19] and to investigate and to compare flow behaviour and its abnormalities in phosporic acid production reactor using ^{131}I isotope [20].

The purpose of the current study is to evaluate of mixing level of single phase flow in a pipeline using radiotracer method. Two basic radiotracer models: axial dispersion model and tanks-in-series model are introduced to predict the mixing level of the flow based on the curve fitting of the residence time distribution (RTD) of experimental data with the RTD simulated from these models. As the model was based on numerical simulation, the best model was justified based on the most minimum error of the curve fitting.

THEORY

Mixing level in a flow system can be approximted by the concept of residence time distribution (RTD). In two extreme ideal flows, either as plug flow reactor (PFR) or as continuously stirred tank reactor (CSTR), the residence time of each fluid particles is same. In real flow, however, the residence time of ach particles in a flow system is not the same and complete velocity distribution of each fluid particle is also not known. It is therefore the knowledge of the distribution of time of each fluid particles spend in a real system (RTD) is needed

for characterization of flow and mixing in the real system. The concept of RTD was early proposed by MacMullin and Weber, but the extensive use of this concept was then used by Danckwerts to describe an important distribution function for studying the flow and the mixing performance of flowing fluids in a non-ideal system such as tubes, mixers and reactors [21]. Book chapter by Fogler has been dedicated to discuss the subject of RTD of mixing in non-ideal reactor [22].

The RTD is commonly obtained by injecting a radioactive isotope instantaneously as a pulse input or at a constant rate as a step input at the inlet of a flow system. For the pulse input, the concentration of injected radioactive isotope measured at the outlet of the flowing system as a function of time is expressed as [11,12]:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \cong \frac{C(t_i)}{\sum_{i=0}^\infty C(t_i)\Delta t_i} \qquad (1)$$

where $C(t)$ is the radioisotope concentration at the outlet as function of time, t. In this regard, other terms such as age-distribution and life expectancy are sometimes interchangeable with residence time. The RTD which describes quantitatively how long time each fluid particle has spent in a continuous flow system is mathematically defined as $E(t).dt$. It represents the fraction of fluid element at the outlet that has spent a time between t and $t + dt$ in the flow system [12]. The total injected radiotracer into the system can be calculated by normalizing the integration of fraction of fluid element from for $t_1 = 0$ to $t_2 = \infty$, or [11,12].

$$\int_0^\infty E(t)dt = 1 \qquad (2)$$

In many cases, the RTD function is expressed in dimensionless time. To do this, the new quantity $\theta = t/\bar{t}$ is introduced, where t is measured time of experiment (s), and $\bar{t}$ is mean residence time (s) of RTD. The consequence of use dimensionless time is that $E(\theta)$ is used instead of $E(t)$. The purpose of creating a dimensionless RTD is that the mixing performance can be better compared at different operating conditions because the mean residence time is eliminated as a variable [23]. The relation of RTD function for both systems is explained by following equation:

$$E(\theta) = \bar{t}E(t) \qquad (3)$$

EXPERIMENTS

The flow rate experiment was carried out at the laboratory of non-destructive testing (NDT), Center for Isotopes and Radiation Application (CIRA), National Nuclear Energy Agency of Indonesia (BATAN). The experiment was carried out by injection of small amount of bromine isotope (^{82}Br) into pipeline of having diameter of 7.62 cm which span around 70 m length containing water flow. The water was supplied from water tank of capacity around 5000 liters. During the experiment, the water tank is maintained containing full of water. The one end of the pipeline is connected to water tank, whereas the other far end is connected to valve. The water flow was due to gravity force on the water only and the volumic flow of water in pipeline was regulated by adjusting valve. The injection point was determined at the point which located around 15 m from the water tank. Around 1 cc of ^{82}Br isotope with activity around 1 mCi was injected manually using plastic syringe into the pipeline. Four collimated scintillation NaI(Tl) detectors (Ludlum Measurment, USA) which placed at the distances of 7, 10, 12 and 15 m respectively from injection point were used to record radiation intensity of injected isotope when it passes the detectors. Prior to injection, these detectors were connected to data-logger and laptop computer. The dummy test was carried out in advanced before performing the real experiment to ensure that the real experiment will be going smoothly and safely. There was no radiation detector placed close to the injection point because this detector would be strongly affected by background radiaion of gamma energy emitted from isotope during transportation of isotope from its container to the injection point and during process of injection itself. The experimental data recorded by the NaI(Tl) scintillation detectors were residence time distribution (RTD) curves of the injected isotope particles in the pipeline. The recorded experimental data were then saved for further data treatment and analysis.

RESULTS AND DISCUSSION

Experimental data of measurement in form of RTD curves is presented in Figure 1. The RTD curve represents the measured radiotracer concentration versus time. The shape of RTD curve including its peak is solely depend on the radiotracer concentration, detector efficiency and geometrical construction of the collimators [25].

The decay correction of radiation intensity was not carried out, because the half-life of the bromine isotope (^{82}Br) is far longer than the time required to do a complete expiment. As it has already known that the half-life of the bromine isotope is 36 hours whereas the time for conducting a complete experiment to obtain RTD data is around 10 minute only. Moreover, the RTD curve was also not necessary be corrected to its background because the radiation intensity of the RTD curve was much higher than the background radiation. In the current study, some physical parameters of fluid flow such as flow rate, mean residence time (MRT), linear or volumic flow rate and the mixing level of fluid are calculated based on the experimental and simulation of RTD curves.
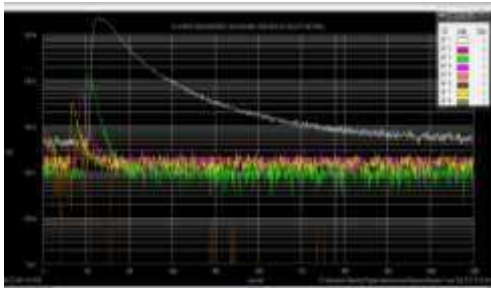

Figure 1. Experimental RTD data obtained from injection of bromine isotope into pipeline containing water flow.

Flow rate calculation.

Flow rate is the most important flow parameter in a flow system. According to the International Standard Organization (ISO), the radiotracer is one of the best alternative techniques for flow rate measurment compared to the conventionl methods such as dye, non-radioactive chemical tracer, and even flow meter [26]. Measurement of water flow in pipeline can be done using radiotracer dilution method and transit time [12,18,19,27]. In this study, the flow rate measurement was calculated based on transit time method through the MRT of the RTD curve because it gives more accurate result [3,12]. MRT or first moment of the RTD curve is defined as [28]:

$$\bar{t} = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt} = \frac{\sum_1^{N_s} tC(t_i)\Delta t_i}{\sum_1^{N_s} C(t_i)\Delta t_i} \qquad (4)$$

where $\bar{t}$ is the first moment of the RTD curve and $C(t)$ is isotope concentration at time t.

The transit time, τ, of isotope moving from detector 1 to detector 2, is calculated using the formula:

$$\tau = \bar{t}_2 - \bar{t}_1 \qquad (5)$$

where $\bar{t}_1$ and $\bar{t}_2$ are the MRT of the first RTD curve and the second RTD curve respectively. To simplify the calculation of transit time, some assumptions were made, namely that the flow system is time-invariant and fully developed flow at the first detector was achieved. Based on these assumptions, the flow rate of water in pipeline was constant [11]. As the flow rate of fluid is constant, therefore only two of four RTD curves are evaluated for flow rate measuement, namely the detector located at the distance of 7 and 10 m from injection point respectively. As the distance of two detectors is 3 m, the flow rate measurement using Eq. (5) was 0.13 m.s^{-1}.

Flow modeling.

Injection of radiotracer into flow system generates experimental RTD data. The RTD data itself is a curve which from mathematical point of view is not a well definite differential function because it is a probability distribution function which describing the time each fluid element resides in the system [11]. In order to be able to predict behavior of system, a mathematical model is needed to be introduced to give meaningful of RTD data. There are two basic mathematical models for RTD analysis in raditracer technology: axial dispersion model and tanks-in-series model. These models are usually employed for flow in non-ideal reactor. By introducing these models, it is understood that the experimental RTD is simulated to produce simulated RTD and it is used to describe the behavior of fluid in the system.

The axial dispersion model was originally used by Danckwerts [21] to describe fluid flow in the system. In this model, the axial motion of the fluid elements consist two components: a convective component arising from bulk motion of the fluid and a diffusive component due to the random motion of the fluid element in responding to the turbulent flow [28]. The simple axial dispersion models is represented by one dimensional Fokker-Plank equation, which describes the evolution of particle distribution in continuous system [29].

$$\frac{\partial C}{\partial \theta} = \frac{D}{uL}\frac{\partial^2 C}{\partial z^2} - \frac{\partial C}{\partial Z} \qquad (6)$$

where D is the axial dispersion coefficient in $m^2.s^{-1}$, z is dimensionless and defined as the ratio of the axial position to the length L of the system. t and $\bar{t}$ are respectively the time and the MRT in s. u is the velocity in $m.s^{-1}$.

Analytical solution of Eq. (8) for different types of boundary conditions are available [17,18,41,46]. For open-open boundary condition as applied in this experiment, the dimensionless solution of Eq. (8) is given by [29]:

$$E(\theta) = \frac{1}{2}\sqrt{\frac{Pe}{\pi\theta}} exp\left\{-\frac{Pe(1-\theta)^2}{4\theta}\right\} \qquad (7)$$

$$\frac{D}{uL} = \frac{1}{Pe} \qquad (8)$$

Where, Pe is the dimensionless Peclet number. Peclet number represents the ratio of flow due to convection in respect to flow due to diffusion. When Pe is close to 1, the flow prefers to follow plug flow, whereas when Pe is close to ∞ the flow prefer to follow perfect mixing.

The tanks-in-series model has been perviously applied to simulate the non-ideal behavior of liquid streams in multiphase system [3]. In this model, the actual volume of a reactor is divided into N equal-sized ideal stirred reactors. The number of tanks is calculated from the following equation [29]:

$$N = \frac{1}{\sigma_\theta^2} \qquad (9)$$

The mean residence time of each reactor is

$$\bar{t}_1 = \bar{t}_2 = \bar{t}_3 \dots = \bar{t}_k \dots = \bar{t}_N = \frac{\bar{t}}{N} \qquad (10)$$

$$\bar{t} = \frac{V_R}{Q} \qquad (11)$$

V_R is the volume of the reactor, Q is the volumic flow and $\bar{t}$ is mean residence time of the real reactor.
The mass balance equation for the kth is [30]:

$$QC_{k-1} = QC_k + \frac{V_R}{N}\frac{dC_k}{dt} \qquad (12)$$

The solution of Eq. (12) can be predicted using Martin method which uses a gamma distribution function [31].

$$E(\theta) = \frac{N(N\theta)^{(N-1)}}{(N-1)!}e^{-N\theta} \qquad (13)$$

Where, N is the total number of stirred tanks.

It is worth to note that some assumptions have been introduced in order to obtain solution of governing equation for axial dispersion model, Eq. (6), and for tanks-in-series model, Eq. (12). These assumptions are applied for both governing equations [28]:
(1)   Steady-state conditions is achieved and maintained over the tracer stimulus test.
(2)   A delta-Dirac tracer pulse insuring that tracer concentration is only function of time and axial position.
(3)   The axial convective velocity and the axial dispersion coefficient of tracer are constant for stable operating condition.
Simulation of experimental RTD data using Eq. (7) for axial dispersion model and Eq. (13) for tanks-in-series model is presented in Figure. 2.
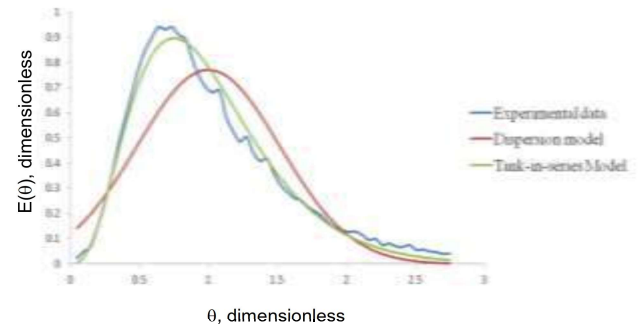

Figure 2. Curve fitting of simulated tanks-in-series model and axial dispersion model on experimental RTD curve.

As can be seen from the figure that the tanks-in-series model gives better curve fitting than that given by the axial dispersion model. The best curve fitting using the tanks-in-series model is achieved when the tank number, N, is 4. This number indicated that the level mixing of fluid in the pipeline is considerable high. In opposite to the axial dispersion model, the property of model parameter for the tanks-in-series model, N, is that when N is close to 1, the flow prefers to follow perfect mixed reactor, whereas when N is close to ∞ , the flow tends to follow plug flow. This result

can be understood, because the tanks-in-series model represents the physical property of continuous stirred tank reactor (CSTR) for which each tank is perfect mixing in character.

Furthermore, the level mixing of water in pipeline can be predicted by the Reynolds number which is formulated as:

$$Re = \frac{ud_h}{v} \qquad (14)$$

where u is flow velocity in m.s^{-1}, d_h is pipe diameter, in m, and v is kinematic viscosity of water which is temperature dependence, in m^3.s^{-1}. The flow velocity calculated used transit time method was 0.13 m.s^{-1}. The pipe diameter is 0.0762 m. The kinematic viscosity of water for temperature of 25°C is 892 x 10^{-9} m^3.s^{-1} [32]. The Reynolds number, Re, for these data is more than 11000 indicates that the water flow in the pipeline is turbulent. This result is to confirm the mixing level predicted by the tanks-in-series model, afore mentioned. From this result, it is confidence to say that the flow behavior of water in the pipeline is best described by the tanks-in-series model and mixing level is considered high. Moreover, this result is good agreement with the previous works [12,18,27].

CONCLUSION

Water flow of single phase in small pipeline of diameter 3 in has been simulated using two basic radiotracer models: the axial dispersion model and tanks-in-series model. The flow rate of water is 0.13 m.s^{-1}, calculated using the transit time method. From simulation, the tanks-in-series model gives better description of flow behavior than axial dispersion model. The best curve fitting is achieved when the model parameter for the tank-in-series model, N, is equal to 4. High value of the calculated Reynolds number indicated that the mixing level of fluid flow is considerable high. This result is to confirm the mixing level predicted by the tanks-in-series model. The experiment concludes that the water flow is best described by the tanks-in-series model and the mixing level of water flow is considerable high.

ACKNOWLEDGEMENT

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PERTANYAAN SAAT PRESENTASI

- **Tidak ada pertanyaan**