Flow Characterization of Vapor Phase of Geothermal Fluid in Pipe Using Isotope ^{85}Kr and Residence Time Distribution Modeling

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A B S T R A C T

Measurement of vapor flow in geothermal pipe faces great challenges due to fast fluids flow in high-temperature and high-pressure environment. In present study the flow rate measurement has been performed to characterization the geothermal vapor flow in a pipe. The experiment was carried out in a pipe which is connected to a geothermal production well, KMJ-14. The pipe has a 10” outside diameter and contains dry vapor at a pressure of 8 kg/cm^2 and a temperature of 170 ^{o}C. Krypton-85 gas isotope (^{85}Kr) has been injected into the pipe. Three collimated radiation detectors positioned respectively at 127, 177 and 227 m from injection point were used to obtain experimental data which represent radiotracer residence time distribution (RTD) in the pipe. The last detector at the position of 227 m did not respond, which might be due to problems in cable connections. Flow properties calculated using mean residence time (MRT) shows that the flow rate of the vapor in pipe is 10.98 m/s, much faster than fluid flow commonly found in various industrial process plants. Best fitting evaluated using dedicated software developed by IAEA expert obtained the Péclet number *Pe* as 223. This means that the flow of vapor of geothermal fluids in pipe is plug flow in character. The molecular diffusion coefficient is 0.45 m^2/s, calculated from the axial dispersion model.

INTRODUCTION

Geothermal energy is a renewable energy source which cases little or almost no pollution. Its resources are distributed throughout the Earth surface, with the greatest concentration being associated with hydrothermal systems in volcanic regions. In nature, geothermal resources are found either in the form of warm groundwater in sedimentary formation or deep water circulation system in crystalline rock [1].

While it is abundantly available, only a very small fraction of geothermal resources can currently be converted commercially into electricity and heating sources with today’s technology. Currently, Indonesia is the world’s third largest geothermal energy producers behind the United States and the Philippines. Today, Indonesia’s installed geothermal electric generating capacity is around 1200 MW from six geothermal fields in Java, North Sumatra and North Sulawesi. By 2025, Indonesia aims to produce more than 9,000 MW of geothermal power, making it the world’s leading geothermal energy producer [2].

Flow rate is one of the most important parameters to be measured in fluid transport pipes. Flow rate measurement of geothermal liquids is in a special class of difficulty because of the low viscosity of the fluids and their high temperature and pressure environment. The common device for volume flow measurement is differential pressure meters such as the orifice plate. The device is inserted into a fluid-carrying pipe, causing an obstruction and creating a pressure difference on either side of the device. The volume flow measurement using orifice plate is inferior in measurement accuracy; hence, such a device should

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be calibrated regularly with a predetermined time interval [3].

The flow of vapor phase of geothermal fluids in pipes can be measured based on residence time distribution (RTD) which was first time introduced by Danckwerts [4]. The RTD concept states that if the flow velocity cannot be obtained because of the unavailability of flow meters, it can be obtained by injecting a suitable radiotracer at the inlet of the system and monitoring its concentration at the outlet of the system. Recorded radiotracer concentrations at the outlet represent how long the radiotracer resides in the system. The obtained RTD data can then be used for calculating the flow rate and analyzing the type of faults which may take place in the system, such as channeling or short-circuiting and the existence of dead volumes.

Among available tracers, gamma emitting radiotracers are the most suitable to be used for industrial applications because their radiation can be detected by using radiation detectors from outside the system with high detection sensitivity and on-line detection can also be performed. Physico-chemical compatibility between the radiotracer and traced materials are available for a wide range of traced materials. Suitable radiotracers are available with various photon energies and they can be chosen to meet the system requirement [5].

Ever since they were introduced, radiotracer techniques have become important tools in various industrial applications. Chemical tracers and radioactive tracers have been used for various research activities both in laboratories and complex industrial plants. Flow rate measurements of geothermal fluids in pipes using various chemical tracers have been reported [6]. Steam flow measurements of geothermal fluids using alcohol tracer have also been conducted and documented [7]. Simulation of injected gamma emitting radiotracer for understanding backward-facing step flow was also performed [8]. Flow behavior of crude oil in a battery of industrial crude oil/gas separators in oil industry was modelled [9]. The influence of inlet positions on the flow behavior inside a photo-reactor has been investigated using radiotracers and colored tracers [10]. Radiotracers for the study of residence time distribution in multiphase flow in Hydrocarbon Transport (HCT) has been studied and reported [11,12]. The same author also used ^{82}Br radiotracer for determination of molecular and turbulent diffusivities in single phase flow of water in small diameter pipes [13]

The purposes of this paper are twofold: First, to report flow rate measurement of vapor phase of geothermal fluids in pipe; and second, to develop an RTD model called the axial dispersion model for analyzing the RTD data obtained from the injection of ^{85}Kr gas isotope with appropriate boundary conditions. The model parameter, the Péclet number (*Pe*), is then used to calculate the molecular diffusion coefficient. Results obtained from this experiment could be used as calibrating tool for the installed flowmeter in a pipe.

GOVERNING EQUATIONS

The vapor phase flow in geothermal pipe is best described by second-order differential equations which are frequently used in fluid mechanics, namely combined diffusion and convection equations. Diffusion process in one dimensional is described by Fick's law which has the form.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{dx} \tag{1}$$

Where *D* is the molecular diffusion coefficient and *C* is the radiotracer concentration. Diffusion process is caused by gradient concentration as described by Eqn. (1). In reality, radiotracer materials injected into vapor flow in pipe are not only diffused but they also move due to the flow of traced materials in a convection process. Therefore, the complete governing equation of vapor phase flow in a geothermal pipe is:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial x^2} \tag{2}$$

where *U* is velocity.

One of the available solutions of Eqn. (2) is obtained by using the concept of residence time distribution (RTD) which was first introduced by Danckwerts [4]. The RTD data can be obtained from the injection of a suitable radiotracer into the inlet of the system followed by the monitoring of the concentration of the radiotracer using radiation detectors placed at the outlet of the system. The injection of the radiotracer should be fast at $t = 0$. If $C(t)$ is the concentration of the radiotracer at the outlet of the system, and assuming that injection at $t = 0$ is described by the Dirac impulse function, then the RTD function $E(t)$ is defined as

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)\,dt} \tag{3}$$

Eqn. (3) calculates the fraction of radiotracer materials still in the system. The integration of denominator represents normalized area which is proportional to the total concentration of radiotracer injected. From Eqn. (3) it follows that the concept of RTD is basically related to the concept of area which can further be exploited using statistical moments [5].

EXPERIMENTAL METHODS

The Kamojang Geothermal site

The Kawah Kamojang geothermal field, located in the Gandapura-Guntur volcanic terrain of West Java and 42 km south east of Bandung, is one of only few dry steam reservoirs in the world which have been developed for energy production. The exploration of geothermal resources in the Kamojang field can be traced back to Dutch colonial era, notified by the first proposal on volcanic energy in 1918. In 1974 the Government of New Zealand drilled five wells in the Kamojang area. Pertamina has continued to drill from 1975 onward and soon installed 30 MW. More wells have been drilled and the Kamojang generating capacity was then expanded from 30 to 140 MW in 1987, supplied by 26 wells. In 2008, the total capacity production of Kamojang geothermal energy reached 200 MW, supplied by 81 wells which comprised four units. A study carried out by Enjineering Kamojang and the Bandung Institute of Technology (ITB) confirmed that the Kamojang geothermal field could be operated with a capacity of up to 230 MW for the next 30 years [14].

Krypton-85 isotope

Krypton-85 (^{85}Kr) isotope has been chosen as radiotracer because it is a noble gas which does not react chemically with the vapor phase of geothermal fluids. Its energy is of medium level which is safe to handle with appropriate containers. The half-life of the ^{85}Kr isotope is very long, so there are no problems with long-distance transportation. As it is in gaseous form, extra care in handling the ^{85}Kr radiotracer is compulsory, otherwise experimental data could not be obtained due to leakage in container or during injection. The properties of the ^{85}Kr isotope are summarized in the Table 1.

Table 1. ^{85}Kr gas radiotracer properties.

Radionuclide	Half time	Energy (keV)	Chemical form
^{85}Kr	10.7 year	γ = 510 β = 840	Gas

Experiment

Flow rate measurements were performed by injecting ^{85}Kr noble gas radioisotope into the 10” diameter geothermal pipe through the sampling point, located within ± 10 m from a geothermal production well, the KMJ-14. ^{85}Kr gas isotope in capsules was supplied by the Center for Radioactive Waste Technology (PTLR), National Nuclear Energy Agency of Indonesia (BATAN). The injection preparation was made by transferring the isotope from a 2500 cm^3 stainless steel capsule into smaller, 500 cm^3 capsules with an activity of ± 650 mCi. The air pressure in the small capsule was increased to 65 kg/cm^2, much higher than the internal pressure in the geothermal pipe which was at the level of 8 kg/cm^2. This strategy was considered as one of the best options in order for the isotope to be able to enter the pipe based on pressure difference. In order to increase the safety factor, an additional highly-pressurized N_2 gas and a small capsule containing freshwater were connected in series through one end of the small capsule. The other end of the small ^{85}Kr capsule was then connected to the injection point through a flexible stainless steel tubing. This network forms an injection system. Prior to injection, a dummy test had been performed in order to make sure that the designed injection system work well as expected.

The injection of ^{85}Kr radiotracer was conducted in a relatively very short time. Three collimated NaI(Tl) radiation detectors (Ludlum Measurement, USA), designated as D1-D3, were placed at the distances of 127, 177 and 227 m from injection point, respectively. The radiation level at the injection point was monitored using an environmental surveymeter. The three detectors were connected to a 12-channel data logger (Ludlum Measurement, USA). The data logger had been set up to record 2400 data points at an interval of 0.05 s. The concentrations of ^{85}Kr radiotracer in the pipe were recorded by the detectors. The complete data, including background levels, was then transferred to the computer and saved for subsequent data analysis and interpretation. The preliminary treatment of the tracer data, which included radiation background subtraction and area normalization, was performed.

RESULTS AND DISCUSSION

The experimental data is presented in Fig. 1. Two of three detectors which are at position 127 and 177 m from injection point had given responses, whereas the third one gave no response. The data represents radiotracer concentration with respect to the measurement time in the pipe. During the time of evolution, the radiotracer concentration may be dispersed due to convection and diffusion processes [15,16].

The data obtained from this experiment is typical in that the radiation intensity of the radiotracer concentration is low in fast flow measurement. The setup of time interval at 0.05 s was intended to get much more data of measurement with the consequence that the radiation intensity of each curve will be low, otherwise the data will be lost. Radiation intensity fluctuations were strongly affected by the dead times of the electronic components of the detector during the pulse shaping formation. The low intensity response at detector D1 can still be distinguished from background level. The non-response of the third detector might be caused by problems in cable connection. However, the available data still gives invaluable information about the investigated flow.

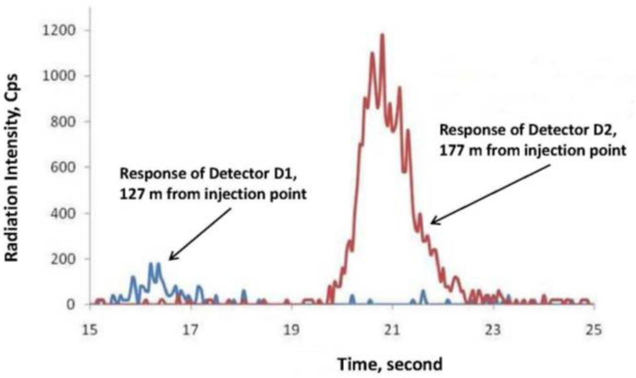

Fig. 1. Experimental data (RTD) at detectors D1 and D2 obtained from injection of ^{85}Kr radiotracer shows fast flow of vapor phase geothermal liquid in pipe.

Flow measurement

Flow measurement theoretically can be calculated using two methods, namely through: (1) peak-to-peak time; and (2) mean residence time (MRT) of each curve. The transit time calculation using the peak-to-peak method is straightforward, namely by measuring the distance between two peak positions of the curves. This method is only suitable for situations where the shape of RTD curve is slim, symmetric, and containing one peak only. In real situations, however, the obtained RTD curves often do not show the ideal shape; therefore, the calculation of flow velocity is best performed through the MRT method which formula is written as [5,17]:

$$\tau = \frac{\int_0^t tC(t)dt}{\int_0^t C(t)dt} \tag{4}$$

Where τ is the mean residence time (MRT), representing the centroid of the RTD curve.

As the system was operated normally during the course of experimental time, it was assumed that the system was time-invariant which means that the values of flow parameters including the volumetric flow were constant. It was also assumed that the flow was steady state. As the distance of the two detectors is definitely known and the inner diameter of the pipe was fixed, the flow velocities of vapor phase of geothermal fluids can be calculated precisely.

To our understanding, the flow rate measurement using radiotracer method was the first attempt in the Kamojang geothermal field to investigate vapor flow characteristics with very high accuracy. Other experimental work have also been performed by others engineers from a private company, namely Thermochem, a specialist in tracer flow tests [6]. They injected various chemical tracers such as fluoride, bromine, fluorescent dye, sodium benzoate, rhodamine WT and naphthalene disulfonate into the pipe for measuring geothermal liquids. As the chemical tracers are unable be recorded on-line even by a specially designed detector, a sampling technique has to be applied to obtain tracer data. Moreover, sampling technique requires a considerable volume of chemical tracers to be injected continuously. Injection of large volumes of chemical tracers may cause instability of the geothermal fluids due to disturbances from the injected chemical tracers. This instability may reduce the accuracy of the measurement.

From this description one can infer that in such flow measurements using chemical tracers, technical-related errors are much more likely, and likely to be greater than the probable errors in flow measurements using radioactive tracers. From this technical point of view, we believed that flow measurements using radioactive tracers should give better result than any other type of flow measurement methods. In many cases, the radiotracer technique can serve as a calibrator for any installed flow meters [17]. Unfortunately however, during the experiment, the flow rate data read-out from the orifice plate installed near the wellhead was not well recorded; therefore, the current flow data cannot be compared with respective data obtained from the installed mechanical device.

Flow modeling

RTD modeling with the so-called axial dispersion model is one of the available methods for the characterization of fluid flow in various tubular reactors such as the one being analyzed in this paper [5,16]. It is worth noting that the RTD data obtained from the experiment cannot give detailed information of flow because the RTD data cannot be exactly defined by any functions exactly; accordingly, an analytical solution cannot be obtained. It is intuitive to introduce a governing equation describing the physical problem of the flow. Concerning this experiment, the vapor flow in geothermal pipe was analyzed using axial dispersion model with Eqn. (2) as the governing equation. This model is the classical model for describing one-dimensional convection and dispersion transport including dependence of radiotracer concentration with time and this model is commonly used for evaluation of fluid flow in tubular reactor such as in the pipe.

In engineering applications, engineers usually use non-dimensional flow quantities for analysis of flow properties. The advantages of using dimensionless quantity is that the balance condition, as a consequence of Eqn. (2), is easily obtained and the measurement no longer depends on the volume or flow rate. In this model the counting time, t, is transformed into dimensionless time, $\theta = t/\tau$, which is called the reduced time. Another flow quantity transformed is Z - $(Ut + x)/L$, which is the distance along the pipe segment. By applying these dimensionless quantities, Eqn. (2) can be written in the form:

$$\left(\frac{D}{UL}\right)\frac{\partial^2 C}{\partial Z^2} - U\frac{\partial C}{\partial Z} = \frac{\Delta C}{\partial \theta} \tag{5}$$

where $C = C(t)/C(0)$ is the radiotracer concentration, which is dimensionless; $Pe = UL/D$ is model parameter, which is called the Péclet number, dimensionless; U is the linear velocity, in m/s; D is the axial dispersion coefficient, or molecular diffusion coefficient, in m^2/s; $C(t)$ is the tracer concentration at time t; $C(0)$ is the tracer concentration at time $t = 0$ and $\theta = t/\tau$ is the reduced time, dimensionless.

A new constant, D/UL in Eqn. (5), is called the dispersion number, which is the reciprocal of the Péclet number, which formulated as UL/D. The Péclet number represents the ratio of transport due to convection to the transport due to diffusion. In the axial dispersion model, the Péclet number is the only model parameter which needs to be calculated. When $UL/D \rightarrow 0$ the flow is represented as well-mixed flow, like flow in stirred continuous tank reactor (CSTR), whereas $UL/D \rightarrow \infty$ the flow is represented as plug flow.

As mentioned previously, the solution of Eqn. (5) depends solely on boundary conditions. One of the most relevant from four available boundary conditions is the open-open boundary condition, as it represents the flow condition in a pipe in which the radiation detector placed is undisturbed. The open-open boundary condition requires $\partial C_\theta / \partial z = 0$ at $z = 0$ and $\partial C_\theta / \partial z = 0$ at $z = L$. By applying these conditions, the solution of Eqn. (5) is [17,18]

$$E(\theta) = \frac{1}{2\sqrt{\pi\theta(D/uL)}}\, exp\left[-\frac{(1-\theta)^2}{4\theta(D/uL)}\right] \tag{6}$$

After formulating the required governing equation and determining the boundary condition, then the modeling process is performed using the IAEA-RTD software which has been developed by the IAEA experts, Thyn and Zidny [19]. This software is a dedicated tool for processing the data obtained from the radiotracer experiment. All radiotracer experimental data are used as input to the software for subsequent processing. In this experiment, the input data is assumed as a narrow pulse (Dirac's delta function) and output data is the RTD data obtained from D2. The RTD data obtained from detector 1 (D1) is not necessary to be processed because the signal is too low. This option will not reduce the analysis quality because the flow properties can be represented either by RTD curves at either D1 or D2 [16]. The task of the software is to perform a parameter optimization processes. The determination of the selected model is based on the best fit with the experimental data. The value of the best fit is judged by choosing the model parameter to minimize the root mean square (RMS) error which is formulated as

$$RMS = \left\{\frac{1}{N_T}\sum |E(\theta) - E_{model}(\theta, parameter)|^2\right\}^{0.5} = minimum \tag{7}$$

Where N_T is the number of processed data points.

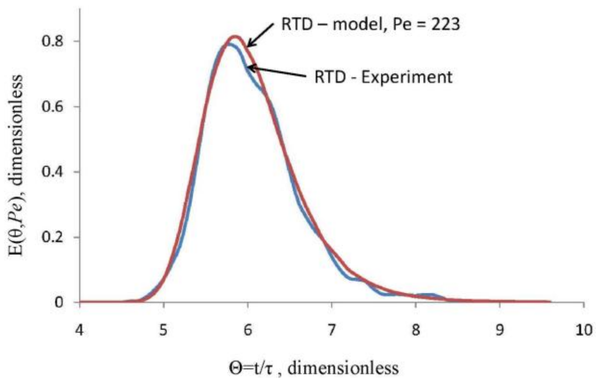

Fig. 2. Fitting curve shows that the axial dispersion model was appropriate for predicting the geothermal vapor flow with fitting error as low as 0.01 only.

The fitting curve between the selected model and the experimental data is presented in Fig. 2. From this simulation, it can be seen that the selected axial dispersion model gives best fit when the Péclet number, *Pe* is 223. By this value it indicates that the vapor flow of geothermal fluids is to follow plug flow in character. Furthermore, the Péclet number also indicates that diffusion process occurred in the vapor flow, with a calculated molecular diffusion equation of 0.45 m^2/s. The value of the Péclet number, which is as high as 223, indicates that the vapor flow in the geothermal pipe due to convection transport far exceeded vapor transport by diffusion. The corresponding error calculated using Eqn. (7) is 0.01, which is extremely low, indicating that the fit was very good and the selected axial dispersion model can be representative of experimental RTD. All calculation results on flow properties are summarized in Table 2.

Table 2. Flow properties of vapor phase of geothermal fluids in pipe.

Transit time, *t (s)*	Distance, *L (m)*	Flow rate, *V (m/s)*	Molecular diffusion coefficient, *D* (m^2/s)
5.5513	50	10.98587	0.4556

To sum up, flow rate measurement using ^{85}Kr radiotracer method was able to reveal the character of the vapor flow of geothermal fluid in the pipe. Calculation of flow velocity through the concept of MRT gives an accurate result. Simulation of experimental RTD data using the axial dispersion model was able to quantize model parameter, *Pe*, based on the best fitting curve with minimum (RMS) error from which the molecular diffusion coefficient of the vapor flow, *D* is calculated.

CONCLUSION

Flow measurements on vapor phase of geothermal fluids in pipe are of a special class of difficulty due to fast fluid flow in high temperature and pressure environment. Through well prepared equipment and procedure this difficulty had been overcome by development of appropriate injection system which enabled the experiment to be performed successfully. The flow rate of the vapor phase of geothermal liquids measured form the injection of ^{85}Kr radiotracer is 10.98 m/s. The Péclet number is 223, obtained from fitting the RTD curve of axial dispersion model to the experimental RTD curve; this value shows that the convection transport dominates the diffusion process, which means that the flow of geothermal vapor in pipe is plug flow. Furthermore, the molecular diffusion coefficient calculated from this model is 0.45 m^2/s, less than one-twentieth of the convection flow. This result can be used as calibrating tool for installed flow meter.

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