Studies on spouting mechanism of a geyser induced by inflow of gas

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Abstract

A geyser is defined as a natural spring that sends hot water and steam intermittently into the air from a hole in the ground. Geysers are classified into two types dependent on inducer. Namely, one is a geyser induced by boiling and the other is a geyser induced by the inflow of gas (a periodic bubbling spring). A geyser induced by the inflow of gas spouts due to pressure of underground gas at the temperature under the boiling point of water. And only a few studies about its mechanism have been proposed. This thesis mainly focuses on solving spouting mechanism of geysers induced by the inflow of gas, especially spouting dynamics of them through mathematical models of them and their numerical simulations. And I also explain various applications for engineering from this study.

In Chapter 2, I explain a static model of a geyser induced by the inflow of gas based on detailed observation of the indoor model experiments. And I confirmed that results of analysis of the model agreed those of the indoor model experiments.

In Chapter 3, I explain a basic dynamical model of a geyser induced by the inflow of gas through detailed observation of the indoor model experiments. And I clarified dependence of spouting dynamics on various underground parameters (volume of the underground space, depth of spouting hole and so on) through numerical simulation of the dynamical model. Then I improved the dynamical model, that is, I took effects of friction between the walls of the spouting pipe and water into account. And I clarified how spouting height was damped by friction between the walls of the spouting pipe and water through numerical simulation of the improved dynamical model. Then I further improved the dynamical model, that is, I add evaporation effect of gas dissolved in hot
spring water during spouting to the dynamical model so as to re-create more practical spouting of a geyser induced by the inflow of gas. And we saw slope of the graph of a top of water pole's temporal variation under \(0\text{[m]}\) (the surface of the earth) is steeper than one over \(0\text{[m]}\) through numerical simulation of the further improved dynamical model. That is characteristic for real spouting of a periodic bubbling spring. And through numerical simulation of the model we also see that the deeper saturated depth is, the steeper slope of the graph under \(0\text{[m]}\) is. Then I further improved the dynamical model. Concretely, I added effects of a complicated underground watercourse and their repeats during spouting to the dynamical model. As a result, I see that in the case of only one pair of sudden expansions and contractions, the effects are not very large, and on the other hand, in the case of many of these pairs or complicated shapes in the underground watercourse, the effects are not negligible. And I also see that the larger the angle of elbow, the larger the degree of transformation in the graph of a top of water pole's temporal variation. Then I showed we could estimate values of underground parameters through comparing spouting dynamics of real geyser induced by the inflow of gas with that of numerical simulation of the dynamical model. As a sample, comparison between numerical simulation of the model and observation of Hirogawara geyser (Yamagata, Japan) was shown.

In Chapter 4, I explain the analysis using both the static model and the dynamical model of a geyser induced by the inflow of gas. The estimation of underground parameters through the analysis make more reliable one because of demands from 2 independent models, that is, the static model and the dynamical model.

In Chapter 5, I explain verification of the models of a geyser induced by the inflow of gas by underground investigation of Kibedani geyser. In conclusion, it is suggested
that underground caves (spaces) which are needed by the model can exist by summing gaps among pebbles and sand in talus deposit as results of indirect geological exploration at Kibedani geyser. And it is suggested that hot spring water gushes through dislocations from an underground deep spot. Finally, it is thought that the static model and the dynamical model are indirectly verified.

In Chapter 6, I developed the dynamical model. Concretely, I proposed a dynamical model which assumed plural underground gas supply sources by extension of above-mentioned usual dynamical model so as to re-create spouting dynamics of a geyser induced by the inflow of gas spouting irregularly. As a result, irregular spouting dynamics was realized through numerical simulation of the dynamical model. And dependence of spouting dynamics of the model on various parameters and each parameter’s effect which brings about irregular spouting were clarified. And comparison between numerical simulation of the model and observation of a geyser induced by the inflow of gas spouting irregularly was also be done.
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Chapter 1

Introduction

1.1 Geysers

A geyser is defined as the natural spring that sends hot water and steam intermittently into the air from a hole in the ground. Geysers are classified into two types dependent on inducer. That is, one is a geyser induced by boiling and the other is a geyser induced by the inflow of gas (a periodic bubbling spring). The former is popular and many ones exist all over the world. Particularly some theories about its mechanism have been proposed [Honda and Terada, 1906]. Moreover their application to other phenomena was also tried [Lorenz, 2002]. Similarly, there are some studies about observation of the former [Husen et al., 2004]. On the other hand, the latter is not popular very much and there are a few ones and only a few studies about its mechanism have been proposed [Iwasaki, 1962].

1.2 Geysers induced by the inflow of gas

Geysers induced by the inflow of gas spout due to pressure of underground gas at the temperature under the boiling point of water. As stated above, a geyser induced by the inflow of gas is not popular very much. For example, it is said that existent geysers induced by the inflow of gas in Japan are just Hirogawara geyser (Yamagata) and Kibedani geyser (Shimane). Therefore, as stated above, only a few studies about its mechanism have been proposed [Iwasaki, 1962].

Examples of spouting dynamics of geysers induced by the inflow of gas are shown in
the following. Fig. 1.1 is an example of spouting dynamics of Kibedani geyser in Shimane (Japan) [Yano, 2000] [Kagami, 2006]. This geyser spouts almost regularly. Fig. 1.2 is an example of spouting dynamics of Hirogawara geyser in Yamagata (Japan) [Endo et al., 1999]. This geyser spouts irregularly. As we see from both figures, a spouting mode and a pause mode appear alternately.

1.3 Earlier studies of spouting mechanism of a geyser induced by the inflow of gas

The spouting mechanism of a geyser has been studied for a long time. But many of these studies were about geysers induced by boiling. Among these studies about geysers induced by boiling, two theories are well-known. One is the cavity theory which was thought by Mackenzie (1912) and extended by Honda and Terada (1905, 1906) and the other is the perpendicular tube theory which was proposed by Bunsen and Descloizeaux (1846) and Bunsen (1847).

On the other hand, there are very few studies of spouting mechanism about geysers induced by the inflow of gas. Then Iwasaki (1944, 1962) constructed experimentally some geyser models of cold waters and gases with cavities shown in Fig. 1.3. These models were none other than experimental models of geysers induced by the inflow of gas. Iwasaki (1944, 1962) conducted many experiments using these geyser models and showed that injection of higher pressure gas spouted water from a spouting spout intermittently. And Iwasaki (1944) described that the geysers of cold waters and gases needed underground cavities and the above-mentioned perpendicular tube theory could not be applied to the geysers of cold waters and gases because these geysers needed space that stored gases.

Then Iwasaki (1944, 1962) estimated spouting time and pause time using the gas
supply rate as a parameter based on the simple calculation of gas balance as follows:

\[ T = T_1 + T_2 \]  

(1.1)

\[ C_1 - C_2 = \int_0^{T_1} L \, dt = \int_0^{T_2} (M - L) \, dt \]  

(1.2)

where \( T_1 \) is pause time, \( T_2 \) is spouting time, \( T \) is one eruption period, \( C_1 \) is the amount of water (or gas) in the geyser system at the beginning of an eruption, \( C_2 \) is the amount of water (or gas) in the geyser system at the end of an eruption, \( L \) is the rate of water (or gas) supply and \( M \) is the rate of water (or gas) discharge. When \( L \) and \( M \) are constant, the following equations are derived:

\[ T_1 = \frac{C_1 - C_2}{L} \]  

(1.3)

\[ T_2 = \frac{C_1 - C_2}{M - L} \]  

(1.4)

\[ T = \frac{(C_1 - C_2)M}{L(M - L)} \]  

(1.5)

\[ \frac{T_2}{T_1} = \frac{L}{M - L} \]  

(1.6)

But above discussion is too simple to estimate the spouting or pause time dependent on various underground parameters. And above discussion does not discuss spouting dynamics of a geyser induced by the inflow of gas. Therefore, the theoretical studies of spouting dynamics related to it as this study are new and meaningful.

1.4 Indoor model experiments of a geyser induced by the inflow of gas

The indoor model experiments of a geyser induced by the inflow of gas were done again in recent years [Katase et al., 1999]. An illustration of the device of the indoor model experiments is shown in Fig. 1.4. The left pipe is for spouting upward and the right pipe is for going downward to the flask. Spouted water from the exit of the left
spouting pipe is returned to the flask through the right pipe to reuse spouted water. When gas is injected sufficiently into a flask, the position of a interface between gas and water in the flask goes down under one of the lower entrance of a left spouting pipe and then water packed in the left pipe spouts owing to pressure of gas in the flask. From the indoor model experiments the following conclusions were clarified:

1. The larger volume of gas in the flask is, the longer spouting period is.
2. The smaller gas supply rate to the flask is, the longer spouting period is.
3. The higher a height from the flask to a spouting exit is, the longer spouting period is.
4. The larger a cross section of the pipe as a watercourse from the flask to a spouting exit is, the longer spouting period is.

But the causes of above experimental results had not been understood yet.

Then through the minute observation of an indoor model experiments [Ishii, 1999] we understood the following new knowledge. Water packed in the left pipe does not spout as soon as the position of the interface between gas and water in the flask goes down under one of the lower entrance of the left pipe. There is a time lag between above two events. Concretely, a surface tension on an interface between water and gas in the lower entrance of the left pipe supports against pressure of gas in the flask for a while. This situation is shown in Fig. 1.5. This characteristics form the core of a later static or dynamical model of a geyser induced by the inflow of gas.

By the way, while space in a flask in the indoor model experiment represents an underground cave, the essential of the space are not shape but the volume of it. That is, even if there is no big space under the ground, the total volume of linked small spaces under the ground is equivalent to the volume of a big space under the ground in the
indoor model experiment and a later static or dynamical model of a geyser induced by the inflow of gas.

1.5 Scope of this thesis

This thesis mainly focuses on solving spouting mechanism of geysers induced by the inflow of gas, especially spouting dynamics of them.

As mentioned above, though there are many studies about a spouting mechanism of a geyser induced by boiling, there are only a few studies about a spouting mechanism of a geyser induced by the inflow of gas because of very few existence of it. Then I mathematically model a spouting mechanism of a geyser induced by the inflow of gas based on the observation of the indoor model experiments. Then I clarify the essentials of the spouting mechanism through numerical simulation of the models. And the indirect verification of the models is done through the underground investigation of a real geyser induced by the inflow of gas.

In chapter 2, I explain a static model of a geyser induced by the inflow of gas. After I introduce an outline of a static model of a geyser induced by the inflow of gas, I compare the static model with the indoor model experiments.

In chapter 3, I explain a dynamical model of a geyser induced by the inflow of gas. At the beginning, I introduce a basic dynamical model of a geyser induced by the inflow of gas. Then I introduce an improved dynamical model \( \cdot 1 \) in which the effects of friction working between the wall's surface along the edge of the paths of water and water are taken into account and discuss it. Then I introduce an improved dynamical model \( \cdot 2 \) in which effects of evaporation of gas dissolved in hot spring water during spouting are taken into account and discuss it. Then I introduce an improved dynamical model \( \cdot 3 \) in
which the effects of a complicated underground watercourse are taken into account and discuss it. Lastly, I introduce application of the dynamical model to a real geyser induced by the inflow of gas.

In chapter 4, I explain the analysis using both the static model and the dynamical model of a geyser induced by the inflow of gas. After I introduce the outline of the analysis, I introduce the results of the analysis through the numerical simulation of the static and dynamical models of a geyser induced by the inflow of gas and discuss them.

In chapter 5, I explain verification of the models of a geyser induced by the inflow of gas by underground investigation of Kibedani geyser. After I introduce the results of various underground investigations, I estimated underground caves and their forming mechanism.

In chapter 6, I explain examples of development of the dynamical model of a geyser induced by the inflow of gas. Concretely, I introduce an improved dynamical model - 4 or 5 in which two or three underground gas supply sources are assumed and discuss it. Then I view application of the improved dynamical model to a real geyser induced by the inflow of gas spouting irregularly.

In chapter 7, I summarized the results.

1.6 What can we explain about real geysers induced by the inflow of gas by the models of a geyser induced by the inflow of gas?

Generally speaking, in case of a geyser induced by the inflow of gas, a spouting mode and a pause mode appear alternately. The period from a spouting mode to a pause mode is made clear by a static model of a geyser induced by the inflow of gas (chapter 2). The dependence of the period on each parameter has been already investigated through
indoor model experiments and the results of that are almost consistent with those predicted through numerical simulation of the static model. Therefore it is conceivable that the static model is an appropriate model of the period from a spouting mode to a pause mode of a geyser induced by the inflow of gas. We can estimate a real set of values of underground parameters by a theoretical set of values of underground parameters which is selected as the result of numerical simulation of the static model almost agrees with that of the observation of a real geyser induced by the inflow of gas on the period from a spouting mode to a pause mode.

The height of a spouting water pole varies with time during a spouting mode of a geyser induced by the inflow of gas. Therefore we need the model which expresses the time variation of height of a spouting water pole during a spouting mode. A basic dynamical model of a geyser induced by the inflow of gas makes clear the dependence of time variation of height of a spouting water pole during a spouting mode on each parameter. The model is also based on the detailed observation of indoor model experiments. Therefore the modeled system is the same as the static model. The dynamical model of a geyser induced by the inflow of gas has been modified by means of adding friction, gas evaporation, complicated underground watercourse, etc. to the basic dynamical model so that the dynamical model nears a real system. The results of numerical simulation of the dynamical model made clear dependence of period, amplitude, etc. on time variation of height of a spouting water pole during a spouting mode on each parameter. We can estimate a real set of values of underground parameters by a theoretical set of values of underground parameters which is selected as the result of numerical simulation of the static model almost agrees with that of the observation of a real geyser induced by the inflow of gas on period, amplitude, etc. of the
time variation of height of a spouting water pole during a spouting mode.

In case of the analysis using both the static model and the dynamical model of a geyser induced by the inflow of gas, the static model or the dynamical model is the model independent of each other. Therefore we can estimate a real set of values of underground parameters independently using each model. We can estimate a real set of values of underground parameters substantially by two models independent of each other using the analysis. This is equivalent to increasing the accuracy of the estimation of a real set of values of underground parameters.

Concerning a geyser induced by the inflow of gas, there are not only one spouting regularly but also one spouting irregularly. In case of a geyser induced by the inflow of gas spouting irregularly we cannot explain its spouting mechanism based on above-mentioned usual dynamical model which assumes single underground gas supply source. Accordingly I proposed the dynamical model which assumes plural underground gas supply sources by the extension of the above-mentioned usual dynamical model. As a result, the irregular spouting dynamics was realized through the numerical simulation of the extended dynamical model.

We can estimate a real set of values of underground parameters by a theoretical set of values of underground parameters which is selected as the result of numerical simulation of the static model almost agrees with that of the observation of a real geyser induced by the inflow of gas using the static model, the dynamical model, the combined model or the extended dynamical model which assumes plural underground gas supply sources depending on the situation.

To verify the existence of underground cavity assumed in each model and so on, indirect observational verification through geological exploration, the analysis of hot
spring water and radioactive prospecting was done. In conclusion, it is suggested that the underground caves (spaces), which are needed by the model, can exist by summing gaps among pebbles and sand in talus deposit as results of indirect geological exploration at Kibedani geyser. And it is suggested that hot spring water gushes through dislocations from an underground deep spot. Finally, it is thought that the combined model is indirectly verified.

From the above, spouting mechanisms of all types of observed geysers induced by the inflow of gas can be explained through the models derived in this study in principle.

From this study, various applications for engineering can be expected. For example, conservation of a geyser system as tourism resources is enumerated. In case spouting weakens at a geyser, appropriate maintenance can be applied to the geyser based on above-mentioned fruits of study in terms of the spouting mechanism of a geyser induced by the inflow of gas.

From the viewpoint of disaster prevention, the change of underground structure can be estimated through numerical simulation of the dynamical model of a geyser induced by the inflow of gas depending on the change of spouting dynamics of the geyser at the time of the disaster such as earthquakes and eruptions.

Moreover this study can be applied to the dynamics of the geyser at the natural nuclear reactor in Oklo (Gabonese Republic) 1.7 billion years ago. In the natural nuclear reactor groundwater penetrated to uranium deposits and groundwater induced fission reaction as a neutron moderator. Then the heat by fission reaction encouraged boiling of water and water spouted. Then cold groundwater penetrated again to the uranium deposits and the same cycle was repeated [Kuroda, 1956] [De Laeter et al., 1980] [Meshik et al., 2004]. In association with the geological disposal of radioactive waste,
which is one of the major challenges of modern engineering, the geological investigation results of the natural nuclear reactor in Oklo give important implications to evaluation of dynamics of the fission product in geologic strata. If my study is applied for the intermittent spouting of water (geyser) at the natural nuclear reactor in Oklo and diffusion of the fission product due to the intermittent spouting of water (geyser) there through the dynamical model of a geyser is elucidated, the analysis through the dynamical model will give more exact evaluation to geological investigation results of the natural nuclear reactor in Oklo.
Fig. 1.1 Temporal variation of height of top of a water pole of Kibedani geyser (Observation) (offered by Maeda lab. at Kanto-Gakuin Univ. (http://home.kanto-gakuin.ac.jp/~kg044001/yano/sub5.shtml))

Fig. 1.2 Temporal variation of height of top of a water pole of Hiogawara geyser (Observation)
Fig. 1.3  Indoor model experiment devices designed by Iwasaki (1944)

Fig. 1.4  An illustration of the device of the indoor model experiments
Flask

A pipe as a watercourse to a spouting exit

An opening is born once just before spouting

Fig. 1.5  An illustration of the situation of just before spouting in the indoor model experiments
Chapter 2

A static model of a geyser induced by the inflow of gas

2.1 An outline of a static model of a geyser induced by the inflow of gas

In this section, I make a static model of a geyser induced by the inflow of gas based on results of indoor model experiments so as to solve relation between the spouting period and each value of various parameters.

As stated above, a water pole packed in the spouting pipe is supported by a surface tension on an interface between water and gas in the lower entrance of the spouting pipe just before spouting as shown in Fig. 2.1. $P_0$, $P$, $H$, $a$, $\alpha$ and $\gamma$ represent the atmospheric pressure, the pressure of gas in the flask, height of a water pole packed in the spouting pipe, a radius of a cross section of the spouting pipe, a contact angle between water and gas in the lower entrance of the spouting pipe and a surface tension on an interface between water and gas in the lower entrance of the spouting pipe, respectively. From relation of pressure balance in the spouting pipe, we get equation (2.1).

$$
S \pi \rho \gamma \cos \alpha + \frac{2 \pi a}{S} = P_0 + \rho g H + \frac{2 \pi \gamma \cos \alpha}{\sqrt{S}}
$$

(2.1)

where $\rho$, $g$ and $S$ represent density of water packed in the spouting pipe, gravitational acceleration and a cross section of the spouting pipe, respectively.

Now we define $V_0$ is volume of gas in the flask over the lower entrance of the spouting pipe and $V'$ is volume of gas between the lower entrance of the spouting pipe
and the surface of the water in the flask as shown in Fig. 2.2. Then an equation of state concerning ideal gas in the flask is written as follows:

\[ P(V_0 + V') = n\alpha' \] (2.2)

where \( n \) represents number of moles of gas in the flask and \( \alpha' \) represents a constant (in case of constant temperature).

Defining gas supply rate to the flask as \( \beta \), we can write the following equation.

\[ \frac{dn}{dt} = \beta \] (2.3)

Now defining the height of a water pole packed in a non-spouting right pipe from the surface of the water in the flask in Fig. 2.2 as \( h \), relation of pressure balance in the non-spouting right pipe is written as follows:

\[ P = P_0 + \rho gh \] (2.4)

Now defining a cross section of the spouting pipe and one of the non-spouting pipe as \( S_A \) and \( S_B \), respectively, the following relations are got.

(i) in case of \( V' \leq 0 \)

\[ dV' = (S_A + S_B)dh \] (2.5)

(ii) in case of \( V' \geq 0 \)

\[ dV' = S_B dh \] (2.6)

Now differentiating equation (2.2) by \( t \) and using equation (2.3), we get the following equation.

\[ (V_0 + V')dP + PdV' = \alpha'\beta dt \] (2.7)

And from equation (2.4), we get the following equation.

\[ dP = \rho gdh \] (2.8)

Now defining the pressure of gas in the flask when height of the lower entrance of the spouting pipe is equal to that of the surface of the water in the flask as \( P_b \), the
following equation is got.

\[ P_b = P_0 + \rho gh_b \]  

(2.9)

where \( h_b \) represents the height of the water pole packed in the non-spouting right pipe from the surface of the water in the flask at that time.

From equation (2.6), when \( V' \geq 0 \), we can write the following equation.

\[ V' = \int_{h_b}^{h} S_h dh = S_h (h - h_b) \]  

(2.10)

Using above equations, we get the following relations in case of \( V' \geq 0 \).

(i) relation between \( t \) and \( h \)

\[ \{V_0 + S_h (h - h_b)\} \rho g dh + (P_0 + \rho gh) S_h dh = \alpha' \beta dt \]  

(2.11)

(ii) relation between \( t \) and \( V' \)

\( (V_0 + V') \rho g \frac{1}{S_h} dV' + \left\{P_0 + \rho g \left(\frac{V'}{S_h} + h_b\right)\right\} dV' = \alpha' \beta dt \)  

(2.12)

(iii) relation between \( t \) and \( P \)

\[ \left[ V_0 + S_h \left\{\frac{1}{\rho g} (P - P_0) - h_b\right\}\right] dP + P \frac{S_h}{\rho g} dP = \alpha' \beta dt \]  

(2.13)

For example, solving equation (2.13), we get the following relation.

\[ P^2 + \left(\frac{\rho g V_0}{S_h} - P_b\right) P = \frac{\rho g \alpha' \beta}{S_h} t + C_0 \]  

(2.14)

where \( C_0 = P_i^2 + \left(\frac{\rho g V_0}{S_h} - P_b\right) P_i \) \( (P_i \) means \( P \) at the time when \( t = 0 \)).

2.2 Comparison of the static model with the indoor model experiments

In this section, I try to interpret the results of the indoor model experiments stated in section 1.4 using above mentioned equations.
(i) relation between volume of gas in the flask and spouting period

In the beginning, we adopt the following variable instead of $t$.

$$\tau = \frac{\rho g \alpha \beta}{S_b} t$$  \hspace{1cm} (2.15)

Using equation (2.14) and (2.15), the following equation is got.

$$\tau = P^2 + \left( \frac{\rho g V_0}{S_b} - P_b \right) P - \left( P_i^2 + \frac{\rho g V_0}{S_b} - P_b \right) P_i$$ \hspace{1cm} (2.16)

Differentiating equation (2.16) by $V_0$, we get the following equation.

$$\frac{d\tau}{dV_0} = \frac{\rho g}{S_b} (P - P_i) > 0$$ \hspace{1cm} (2.17)

This equation shows that the larger $V_0$ (volume of gas in the flask) is, the longer $\tau$ (spouting period) is.

(ii) relation between gas supply rate to the flask and spouting period

From equation (2.15) and (2.16), we get the following equation.

$$t = \frac{S_b}{\rho g \alpha \beta} \left[ P^2 + \left( \frac{\rho g V_0}{S_b} - P_b \right) P - \left( P_i^2 + \frac{\rho g V_0}{S_b} - P_b \right) P_i \right]$$ \hspace{1cm} (2.18)

This equation shows that the smaller $\beta$ (gas supply rate to the flask) is, the longer $t$ (spouting period) is.

(iii) relation between a height from the flask to a spouting exit and spouting period

In the beginning, applying equation (2.1) and $h_b = H$ to equation (2.18), we get

the following equation.

$$t = \frac{S_b}{\rho g \alpha \beta} \left[ \left( P_0 + \frac{\gamma \cos \alpha \cdot 2\sqrt{\pi}}{\sqrt{S_A}} + \rho g H \right)^2 - P_i^2 \right]$$

$$+ \left( \frac{\rho g V_0}{S_b} - (P_0 + \rho g H) \right) \left( P_0 + \frac{\gamma \cos \alpha \cdot 2\sqrt{\pi}}{\sqrt{S_A}} + \rho g H - P_i \right)$$ \hspace{1cm} (2.19)
Differentiating equation (2.19) by $H$, we get the following equation.

\[
\frac{dt}{dH} = \frac{S_B}{\rho g \alpha' \beta} \left[ 2 \left( P_0 + \frac{\gamma \cos \alpha \cdot 2\sqrt{x}}{\sqrt{S_A}} + \rho g H \right) \rho g - \left( P_0 + \frac{\gamma \cos \alpha \cdot 2\sqrt{x}}{\sqrt{S_A}} + \rho g H - P_1 \right) \rho g \right] \\
+ \left[ \frac{\rho g V_0}{S_B} - (P_0 + \rho g H) \right] \rho g \\
= \frac{S_B}{\alpha' \beta} \left( P_1 + \frac{2\sqrt{x} \gamma \cos \alpha}{\sqrt{S_A}} + \frac{\rho g V_0}{S_B} \right) > 0 \tag{2.20}
\]

This equation shows that the higher $H$ (a height from the flask to a spouting exit) is, the longer $t$ (spouting period) is.

(iv) relation between a cross section of the pipe as a watercourse from the flask to a spouting exit and spouting period

In the beginning, we think dividing the situation into two cases.

(i) in case of $V' \leq 0$

From equation (2.5), we get the following equation.

\[ V' = (S_A + S_B)(h - h_b) \tag{2.21} \]

Therefore replacing $S_B$ with $S_A + S_B$ in equation (2.18), we get the following equation.

\[ t = \frac{S_A + S_B}{\rho g \alpha' \beta} \left( P_1^2 - P_1 \right) + \left( \frac{\rho g V_0}{S_A + S_B} - P_1 \right)(P - P_1) \tag{2.22} \]

Differentiating equation (2.22) by $S_A$, we get the following equation.

\[
\frac{dt}{dS_A} = \left( P_1^2 - P_1 \right) \frac{P_1(P - P_1)}{\rho g \alpha' \beta} - \frac{P_1(P - P_1)}{\rho g \alpha' \beta} \\
= \frac{(P - P_1)(P + P_1 - P_b)}{\rho g \alpha' \beta} \tag{2.23}
\]

Here because $P + P_1 - P_b \geq 2P_1 - P_b$ is realized in equation (2.23), I see that in case of
\[ P_i \geq \frac{1}{2} P_b, \quad \frac{dt}{dS_A} \geq 0 \] is realized and in case of \( P_i \leq \frac{1}{2} P_b, \quad \frac{dt}{dS_A} \leq 0 \) is realized.

From these equations, I see that in case of \( P_i \geq \frac{1}{2} P_b \), the larger \( S_A \) (a cross section of the pipe as a watercourse from the flask to a spouting exit) is, the longer \( t \) (spouting period) is, and in case of \( P_i \leq \frac{1}{2} P_b \), the larger \( S_A \) is, the shorter \( t \) is. Since it is thought that \( P_i \geq \frac{1}{2} P_b \) is realized in most cases, \( \frac{dt}{dS_A} \geq 0 \) will be realized in most cases.

(ii) in case of \( V' \geq 0 \)

Transforming an equation derived after equation (2.1) is substitute for equation (2.14), we get the following equation.

\[
t = \frac{S_b}{\rho g \alpha \beta} \left( P_0 + \rho g H + \frac{2\sqrt{\pi} \gamma \cos \alpha}{\sqrt{S_A}} - P_i \right)
\]

\[
\times \left( P_0 + \rho g H + \frac{2\sqrt{\pi} \gamma \cos \alpha}{\sqrt{S_A}} + P_i + \frac{\rho g V_0}{S_B} - P_b \right) \tag{2.24}
\]

Differentiating equation (2.24) by \( S_A \) and using equation (2.9), we get the following equation.

\[
\frac{dt}{dS_A} = -\frac{S_b}{\rho g \alpha \beta} \sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{3}{2}} \left( P_0 + \rho g H + 2\sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{1}{2}} + P_i + \frac{\rho g V_0}{S_B} - P_b \right)
\]

\[
+ \left( P_0 + \rho g H + 2\sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{1}{2}} - P_i \right)
\]

\[
= -\frac{S_b}{\rho g \alpha \beta} \sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{3}{2}} \left( 2P_0 + 2\rho g H + 4\sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{1}{2}} + \frac{\rho g V_0}{S_B} - P_b \right)
\]

\[
= -\frac{S_b}{\rho g \alpha \beta} \sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{3}{2}} \left( P_0 + 2\rho g H + 4\sqrt{\pi} \gamma \cos \alpha S_A^{-\frac{1}{2}} + \frac{\rho g V_0}{S_B} - \rho g h_b \right)
\]
This equation shows that the larger $S_A$ (a cross section of the pipe as a watercourse from the flask to a spouting exit) is, the shorter $t$ (spouting period) is.

Consequently, a power relationship between case (i) and case (ii) finally decides if spouting period is longer when a cross section of the pipe as a watercourse from the flask to a spouting exit is larger. Because the time when $V' \leq 0$ is usually longer than that when $V' \geq 0$ in case of normal spouting of geyser induced by the inflow of gas, in most cases $t$ (spouting period) will be longer when $S_A$ (a cross section of the pipe as a watercourse from the flask to a spouting exit) is larger.

These results are in good agreement with the indoor experimental results stated above.
Fig. 2.1 An illustration of the situation of the spouting pipe just before spouting in the indoor model experiments
Fig. 2.2 An illustration of the situation of just before spouting in the indoor model experiments.
Chapter 3

A dynamical model of a geyser induced by the inflow of gas

3.1 A basic dynamical model of a geyser induced by the inflow of gas

From the results of the above mentioned indoor model experiments of the geyser induced by the inflow of gas, I understood that a beginning of spouting is made by the loss of surface tension supporting a lump of water packed in a pipe leading to a spouting exit. Namely, in the model experiments the underground situation shown in Fig 3.1 is assumed. A spouting hole is deep and leads to a space where gas and water are supplied at a constant rate at the deep position under the ground. Before a beginning of spouting pressure of gas in the space is supported by surface tension on the lower interface between water and gas (and gravity acting on the mass of a lump of water packed in the hole (pipe) and the pressure of the atmosphere). But when a value of pressure of gas in the space becomes larger than a threshold, the surface tension comes not to be able to support pressure of gas in the space. Then a lump of water packed in a pipe leading to a spouting exit begins to move up to the exit on the ground. In a basic dynamical model of a geyser induced by the inflow of gas, the dynamics of a lump of water packed in the pipe is discussed.

When the pressure of gas in the space just before a lump of water’s beginning to move up to the exit on the ground is put as $p_i$, $p_i$ is represented as:

$$p_i = p_0 + \rho g H + f_k$$ (3.1)

where $p_0$ represents the pressure of the atmosphere, $\rho$ represents density of water, $g$ represents gravity acceleration, $H$ represents length of a lump of water packed in
the pipe from the lower interface between water and gas to the upper one and \( f_k \) represents pressure due to surface tension on the lower interface between water and gas. And \( f_k \) is represented as:

\[
f_k = \frac{2\sqrt{\pi \gamma \cos \alpha}}{\sqrt{S}}
\]

(3.2)

where \( \gamma \) represents a coefficient of surface tension, \( \alpha \) represents contact angle and \( S \) represents an area of a cross section of the pipe filling a lump of water. Namely, equation (3.1) is the same as equation (2.1).

When a lump of water packed in the hole begins to move up, \( f_k \) is regarded as \( f_k \rightarrow 0 \). Then when an upper direction of a vertical line is regarded as a plus direction of \( x \)-axis, an equation of motion of the lump of water is written as:

\[
p\rho SH \frac{d^2 x}{dt^2} = pS - \rho gSH - p_0 S
\]

(3.3)

where \( p \) represents the pressure of gas in the underground space. Here, \( x \) is regarded as a position of the lower interface between water and gas of the water pole and friction between the walls of the pipe and water is ignored.

When it is assumed that gas in the underground space is ideal gas and changes isothermally,

\[
d\left( \frac{pV}{n} \right) = 0
\]

(3.4)

where \( V \) represents volume of gas filled in the underground space and \( n \) represents molar number of it is realized.

From equation (3.4),

\[
npdV + nVdp - pVdn = 0
\]

(3.5)

is derived.

When it is assumed that \( x = 0 \) and \( V = V_0 \) just before the lump of water begins to
move up, we can write $V$ as:

$$V = V_0 + Sx$$ \hfill (3.6)

From equation (3.6),

$$dV = Sdx$$ \hfill (3.7)

is derived.

From the assumption that gas is supplied at a constant rate in the underground space,

$$\frac{dn}{dt} = \beta$$ \hfill (3.8)

where $\beta$ is constant is derived. From equation (3.8), $n$ can be represented as:

$$n = n_0 + \beta t$$ \hfill (3.9)

where $n_0$ represents molar number when $p = p_i$ and $V = V_0$. On this account we can write using equation (3.1) as:

$$n_0 = \frac{p_i V_0}{RT} = \frac{V_0 (p_0 + \rho g H + f_k)}{RT}$$ \hfill (3.10)

Applying equation (3.6) - (3.9) to equation (3.5),

$$(n_0 + \beta t)pS \frac{dx}{dt} + (n_0 + \beta t)(V_0 + Sx)\frac{dp}{dt} = (V_0 + Sx)p\beta$$ \hfill (3.11)

is derived. And from equation (3.3),

$$\frac{dp}{dt} = \rho H \frac{d^3 x}{dt^3}$$ \hfill (3.12)

is derived. From equation (3.11) and (3.12) we can get

$$(n_0 + \beta t)(V_0 + Sx)\rho H \frac{d^3 x}{dt^3} + (n_0 + \beta t)pS \frac{dx}{dt} = (V_0 + Sx)p\beta$$ \hfill (3.13)

$x$, that is, a position of the lower interface between water and gas of the water pole moves obeying equation (3.13).

In general, the effects of surface tension are smaller with decreasing space size.
Therefore, in this model, it is assumed that the actual gate connecting the spouting pipe and the underground space is enough small and doesn’t resemble the expansion of the shape shown in Fig 3.1. It is thought that large volume of the underground space consists of the sum of small volume of the underground small caves which are connected each other by a network. This assumption is indirectly supported through video observations inside the conduits of erupting geysers by Belousov et al. (2014).

Then I show some results of numerical simulation of the basic dynamical model of a geyser induced by the inflow of gas as follows.

**Table 3.1 Adopted values of parameters in numerical simulations**

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_k$</td>
<td>$2.24 \times 10^{-1}$ [N/m²]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$1.0 \times 10^3$ [kg/m³]</td>
</tr>
<tr>
<td>$S$</td>
<td>$1.0 \times 10^{-2}$ [m²]</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$1.01 \times 10^5$ [N/m²]</td>
</tr>
<tr>
<td>$g$</td>
<td>$9.8 \times 10^9$ [kg·m/s²]</td>
</tr>
<tr>
<td>$V_0$</td>
<td>$6.0 \times 10^4$ [m³]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$1.0 \times 10^{-3}$ [mol/s]</td>
</tr>
<tr>
<td>$R$</td>
<td>$8.31 \times 10^0$ [N·m/K/mol]</td>
</tr>
<tr>
<td>$T$</td>
<td>$3.20 \times 10^2$ [K]</td>
</tr>
</tbody>
</table>

In the beginning, I show the dependence of variation of height of a water pole ($x$) on length (height) of a water pole ($H$) during spouting in Fig. 3.2. Adopted values of parameters are shown in Table 3.1. The values are decided based on expected values. $f_k$ is calculated using equation (3.2) in case of $\alpha=30^\circ$ and $S=1$[m²]. In this case, $S$ represents not an area of a cross section of the pipe filling a lump of water in the experimental system but an expected area of a cross section of a pipe connected just to the real underground space. On the other hand, the value of $S$ in Table 3.1 represents an expected value (close to the observed value) of a cross section of the spouting pipe. And the value of $V_0$ represents the expected sum of small volume of the underground.
small caves which are connected each other by a network, as described above. And the value of $\beta$ is estimated based on the total volume of spouted water during a spouting mode at a real geyser induced by the inflow of gas. While spouted water is removed from the water pole during spouting, the water is not removed from the water pole before spouting. From Fig. 3.2, we see that the higher a water pole ($H$) is, the smaller an amplitude of the water pole’s oscillation is and the longer a spouting period (a period of the water pole’s oscillation) is.

Then I show the dependence of variation of height of a water pole ($x$) on length (height) of a water pole ($H$) before spouting in Fig. 3.3. Adopted values of parameters are the same as ones sown in Table 3.1. The characteristics seen from Fig. 3.3 resemble ones seen from Fig. 3.2. But the characteristics are a little different from ones seen from Fig. 3.2 because there is a loss of a water pole due to water’s spouting in case of the former.

The difference is shown in Fig. 3.4. $h$ in a legend of Fig. 3.4 means a length (height) between a spouting exit and the upper surface of a water pole at the beginning. Though in case of $h=30$ the spouting has not started yet in the figure, in case of $h=3$ the spouting has already started. And the length (height) of water poles ($H$) before spouting is same in both cases. From Fig. 3.4, we see that spouting period becomes shorter after spouting began. For substantial length (height) of water poles ($H$) becomes shorter after spouting begins.

Next, I show the dependence of variation of height of a water pole ($x$) on pressure due to surface tension on the lower interface between water and gas ($f_k$) in Fig. 3.5. Adopted values of parameters are the same as ones shown in Table 3.1 except for the value of $f_k$ and $H=100$[m]. From Fig. 3.5, We see that the larger pressure due to
surface tension on the lower interface between water and gas ($f_k$) is, the larger an amplitude of the water pole’s oscillation is. For $f_k$ represents strength to push up a water pole. On the other hand, spouting period does not depend on $f_k$ because $f_k$ has an effect on only strength pushing up a water pole.

Next, I show the dependence of variation of height of a water pole ($x$) on volume of underground space ($V_0$) in Fig. 3.6. Adopted values of parameters are the same as ones sown in Table 3.1 except for the value of $V_0$ and $H = 100$ [m]. Incidentally it may be thought that $f_k$ is pressure due to not only above-mentioned surface tension but also other power. From Fig. 3.6, we see that the larger volume of underground space ($V_0$) is, the larger an amplitude of the water pole’s oscillation is and the longer a spouting period is. Namely, the volume of underground space ($V_0$) affects both an amplitude of the water pole’s oscillation and a spouting period greatly.

### 3.2 An improved dynamical model - 1 in which effects of friction working between the wall’s surface along the edge of the paths of water and water are taken into account

In the improved dynamical model – 1, I take the effects of friction between the walls of the spouting pipe and water into account. The concrete methods of introduction of the effects of friction are explained in the following.

Taking effects of friction between the walls of the spouting pipe and water into account means that we regard a water pole packed in the spouting pipe as viscous fluid. If we formally assume the water pole as viscous fluid, we have to consider friction between water and water in the water pole. That means considering dynamics of viscous fluid and a subject will become much complicated.
So I consider pseudo-friction effects in which only friction between the walls of the spouting pipe and water is taken into account. Actually, because viscous fluid flowing in a circular pipe obeys Poiseuille's law which argues friction between the walls of the spouting pipe and water is largest in the circular pipe, the pseudo-friction effects are not beside the mark very much.

In the beginning, in numerical experiments solving an equation of motion of the water pole clarify its velocity at a moment. From the velocity and an area of cross section of the pipe $S$, flux of fluid $V_f$ is derived.

On the other hand, from Poiseuille's law distribution of velocity $u$, of fluid is represented as:

$$u = B(a^2 - r^2) \quad (3.14)$$

where $a$ represents a radius of the spouting pipe, $r$ represents length from the center of a cross section of the spouting pipe to the direction perpendicular to the wall of the pipe and $B$ is coefficient. Calculating flux $V_B$ of fluid from equation (3.14),

$$V_B = \int_0^a 2\pi r u dr = \frac{\pi B a^4}{2} \quad (3.15)$$

is derived. From equation (3.15),

$$B = \frac{2V_B}{\pi a^4} \quad (3.16)$$

is derived.

While, from equation (3.14),

$$\frac{du}{dr} = -2Br \quad (3.17)$$

is derived. Therefore we can get

$$\frac{du}{dr} \bigg|_{r=a} = -2Ba \quad (3.18)$$
On the other hand, inner friction force $f$ is written as:

$$f = \eta A \frac{du}{dr}$$  \hspace{1cm} (3.19)

where $\eta$ represents viscosity coefficient and $A$ represents an area where water keeps in touch with a wall of a pipe or water.

From

$$V_f = V_B$$  \hspace{1cm} (3.20)

and equation (3.16), (3.18) and (3.19), we can write friction force $f_w$ between the wall of the pipe and water as:

$$f_w = \frac{8\eta \pi H V_f}{S}$$  \hspace{1cm} (3.21)

Furthermore, a direction of friction force $f_w$ is opposite to that of velocity of the water pole $\frac{dx}{dt}$.

Then a term of friction force $f_w$ is added to an equation of motion of the lump of the water (equation (3.3)). Hereafter the same discussion as that in the basic dynamical model is developed.

Concretely, we can write

$$V_f = S \frac{dx}{dt}$$  \hspace{1cm} (3.22)

Noticing a sign of $f_w$, from equation (3.3), (3.21) and (3.22) we get

$$\rho SH \frac{d^2 x}{dt^2} = pS - \rho g SH - p_o S - f_w$$

$$= pS - \rho g SH - p_o S - 8\pi \eta H \frac{dx}{dt}$$  \hspace{1cm} (3.23)

From equation (3.23), we get

$$\rho SH \frac{d^3 x}{dt^3} = S \frac{dp}{dt} - 8\pi \eta H \frac{d^2 x}{dt^2}$$  \hspace{1cm} (3.24)
Finally, from equation (3.11) and (3.24) we get

\[ (n_0 + \beta t)(V_0 + Sx)\rho H \frac{d^2 x}{dt^2} + \frac{8\pi \eta H}{S} (n_0 + \beta t)(V_0 + Sx)\frac{d^2 x}{dt^2} + (n_0 + \beta t)pH \frac{dx}{dt} = (V_0 + Sx)p \beta \]

(3.25)

Second term of equation (3.25) is a newly added term that represents effects of friction between the walls of the pipe and water.

Then I show the results of numerical simulation of the improved dynamical model - 1 of a geyser induced by the inflow of gas as follows.

The difference of variation of height of a water pole \( x_0 \) from start to 800 second after between in case of friction's existing (this improved model) and in case of no friction is shown in Fig. 3.7. From Fig. 3.7, we see that if there is friction, the amplitude of the water pole's oscillation becomes smaller as time passes. Then the same graph from 900 second after to 1400 second after from the start is shown in Fig. 3.8. We cannot see downward movement of a water pole almost after 1000 second after from the start if there is friction. This variation of height of a water pole resembles spouting dynamics of a geyser that involves no water pole's oscillation.

3.3 An improved dynamical model - 2 in which effects of evaporation of gas dissolved in hot spring water during spouting are taken into account

In this section, I add an evaporation effect of gas dissolved in hot spring water during spouting to the dynamical model of a geyser induced by the inflow of gas so as to re-create more practical spouting of a geyser induced by the inflow of gas. When hot spring water goes up from underground deep region during spouting mode, the vapor pressure of gas dissolved in it saturates in time before it reaches a spouting spout because of a drop in pressure. As a result, the dissolved gas evaporates one after
another in various places where the vapor pressure of it saturates and the volume of hot spring water and the evaporated gas packed in a spouting hole increases greatly. These phenomena may affect spouting dynamics of a geyser very much. In this study, I take the effects of increase of volume of hot spring water and the evaporated gas packed in a spouting hole into account.

In the beginning, I explain the introduction of evaporation effect of gas dissolved in hot spring water during spouting to the dynamical model. When hot spring water goes up from deep underground region during spouting mode, the vapor pressure of gas dissolved in it saturates in time before it reaches a spouting spout because of a drop in pressure as mentioned above. Or in the first place, the hot spring water of a geyser induced by the inflow of gas may be a saturated solution of gas in underground deep region. I can give following two examples as the evidences of above conjectures.

1. Underground caves (spaces) are filled by gas. This is one of important elements in all models of geyser induced by the inflow of gas.

2. Spouting hot spring water includes bubbles of gas. A snap shot of beginning of spouting at Kibedani Geyser (Shimane, Japan) is shown in Fig. 3.9. This snap shot enables us to understand above fact.

As a result, the dissolved gas evaporates one after another in various places where vapor pressure of it saturates and the volume of hot spring water and the evaporated gas packed in a spouting hole increases greatly. So we estimate the effects of increase of volume of hot spring water and the evaporated gas packed in a spouting hole.

In the beginning, it is assumed that dissolved gas is CO$_2$, $T=40[^\circ C]$ and volume of dissolvable CO$_2$ in 1cm$^3$ of water under any pressure is 0.53[cm$^3$] for simplicity. Therefore, when a saturated solution of CO$_2$ at $h'$ in depth goes up $x$ in height, CO$_2$
of
\[
\left(1 - \frac{\rho g (h' - x) + P_0}{\rho g h' + P_0}\right) \times 0.53 \text{[cm}^3\text{]} \tag{3.26}
\]
in volume is extracted per in 1cm\(^3\) of water. Integrated volume of above extracted CO\(_2\) concerning all height is increased volume of a lump of water and gas packed in the spouting pipe.

In general, volume of extracted gas is written as:
\[
\left(1 - \frac{\rho g (h' - x) + P_0}{\rho g h' + P_0}\right) \times a \tag{3.27}
\]
where \(a\) represents the volume of dissolvable gas. These effects are added to the above dynamical model.

Then I show some results of numerical simulation of the modified dynamical model and discuss them. In the beginning, the temporal variation of a top of a water pole depended on \(a\) is shown in Fig. 3.10. We can see the slope of the graph of a top of water pole’s temporal variation under 0[m] (the surface of the earth) is steeper than one over 0[m]. That is characteristic for real spouting of a periodic bubbling spring (see Fig. 1.1). And the larger \(a\) is, the steeper slope of the graph under 0[m] is. For the larger \(a\) is, the larger total volume of dissolved gas as shown in equation (3.27) is.

And temporal variation of a top of a water pole also changes dependent on the depth in which gas solution saturates. This situation is shown in Fig. 3.11. We can see that the deeper saturated depth is, the steeper slope of the graph under 0[m] is. For the deeper saturated depth is, the larger total volume of dissolved gas.

In conclusion, I derived the modified dynamical model to which evaporation effect of gas dissolved in hot spring water during spouting was added. Then I introduced some
results of numerical simulation of the modified combined model and discussed the effects of increase of total volume of hot spring water and the evaporated gas packed in the spouting pipe.

After this, quantitative comparison with observational data will be needed.

3.4 An improved dynamical model - 3 in which effects of a complicated underground watercourse are taken into account

In this study, I add the effects of a complicated underground watercourse during spouting to the dynamical model so as to re-create more practical spouting of a geyser induced by the inflow of gas. In the case of the former models, it was assumed that the underground watercourse was vertically straight for simplicity. Practically the measurable underground watercourses of geysers induced by the inflow of gas are almost straight because of past remains of boring and so on. But it is expected that the underground watercourse has a complicated shape at deep underground region. And for example a curved shape, a taper one or other one give a kind of resistance. In this study, in the beginning I add the resistances of sudden expansion and sudden contraction to the former model as an example and discuss effects of them quantitatively through numerical simulation of the extended model.

Here I introduce effects of resistances of sudden expansion and sudden contraction as an example of a complicated underground watercourse. For it is thought that sudden expansion and sudden contraction can be frequently seen in underground watercourses. By the way, effects of other resistances can also be dealt with similarly.

Now for the sake of simplicity I assume the spouting pipe is cylindrical. Sudden expansion and sudden contraction are shown in Fig. 3.12 and 3.13, respectively. $D_r$ or
$D_2$ represents a diameter of a wide part of a pipe or one of a narrow part of it respectively in each figure. And $V_1$ or $V_2$ represents velocity of a flow in a wide part of the pipe or one in a narrow part of it then respectively in each figure. A shape of sudden expansion is the same as one of sudden contraction as shown in both figures. But though in the case of the former water flows from a narrow part of the pipe to a wide one, in the case of the latter water flows from a wide part of the pipe to a narrow one, reversely. For example, if hot spring water passes a sudden contraction region when it flows upward, the region replaces a sudden expansion region when it flows downward.

Next I discuss loss water head of these singular shapes. Loss water head of sudden expansion $h_{se}$ and that of sudden contraction $h_{sc}$ are defined using loss coefficient of sudden expansion $K_{se}$ and that of sudden contraction $K_{sc}$ respectively as:

\[
h_{se} = K_{se} \frac{V_1^2}{2g}
\]

\[
h_{sc} = K_{sc} \frac{V_2^2}{2g} = K_{sc} \left( \frac{D_1}{D_2} \right)^4 \frac{V_1^2}{2g}
\]

(3.28)

(3.29)

where $g$ represents gravity acceleration.

Now we assume the direction from a wide part of the pipe to a narrow one, that is, the direction of an up-pointing arrow in Fig. 3.12 coincides with the vertically upward direction. A spouting mode begins when the surface tension on the interface between the water packed in the spouting pipe and the gas in the underground cave (and weight of a small volume of water packed in the spouting pipe and pressure of the atmosphere) becomes smaller than the pressure of gas in the underground cave. Then an equation of motion of the small volume of water is written as equation (3.3). Adding the effects of a sudden contraction and expansion to the former model in equation (3.3), we get the following equations.
In the case of \( \frac{dx}{dt} \geq 0 \)

\[
\rho SH \frac{d^2 x}{dt^2} = pS - \rho g SH - p_o S - \rho g Sh_s
\]  
(3.30)

(2) In the case of \( \frac{dx}{dt} \leq 0 \)

\[
\rho SH \frac{d^2 x}{dt^2} = pS - \rho g SH - p_o S - \rho g Sh_s
\]  
(3.31)

Finally, we arrive at the following equations to replace equation (3.13).

(1) In the case of \( \frac{dx}{dt} \geq 0 \)

\[
(n_o + \beta)(V_o + Sx)pH \frac{d^3 x}{dt^3} + (n_o + \beta)(V_o + Sx)pK_s \left( \frac{D_2}{D_1} \right)^4 \frac{dx}{dt} \frac{d^2 x}{dt^2} + (n_o + \beta)pS \frac{dx}{dt} = (V_o + Sx)p\beta
\]  
(3.32)

(2) In the case of \( \frac{dx}{dt} \leq 0 \)

\[
(n_o + \beta)(V_o + Sx)pH \frac{d^3 x}{dt^3} + (n_o + \beta)(V_o + Sx)pK_s \left( \frac{D_2}{D_1} \right)^4 \frac{dx}{dt} \frac{d^2 x}{dt^2} + (n_o + \beta)pS \frac{dx}{dt} = (V_o + Sx)p\beta
\]  
(3.33)

Equations (3.32) and (3.33) are basic equations that include the effects of a sudden contraction and expansion.

Then I show some results of numerical simulation of the above extended dynamical model and discuss them. Following values of parameters are given. \( V_o = 9.90 \times 10^5[\text{m}^3] \), \( \rho = 1.00 \times 10^3[\text{kg/m}^3] \), \( g = 9.80 \times 10^3[\text{kg/m/s}^2] \), \( H = 1.00 \times 10^3[\text{m}] \), \( \beta = 1.90 \times 10^{-4}[\text{mol/s}] \) and \( S = 1.00 \times 10^{-2}[\text{m}^2] \). \( n_o \) is calculated using equation (3.10) when \( p_o = 1.01 \times 10^5[\text{Pa}] \) and \( f_s = 2.20 \times 10^4[\text{N/m}^2] \). Each model equation is simulated numerically using Runge-Kutta method.

Here temporal variation of a top of a water pole depended on the ratio of \( D_2 : D_1 \), that is, \( \frac{D_2}{D_1} \) is shown in Fig. 3.14. And corresponding values of \( K_s \) and \( K_{sc} \) in
case of each \( D_2 : D_1 \) are shown in Table 3.2. In the beginning, we can see that the larger the ratio of \( D_2 : D_1 \) is, the shorter period of height's oscillation is. And we can also see that the larger the ratio of \( D_2 : D_1 \) is, the larger amplitude of height's oscillation is. The reason why above 2 tendencies occur is common. That is, because the smaller the ratio of \( D_2 : D_1 \) is, the larger values of \( K_{sc} \) and \( K_{se} \) are, consequently effects of resistances are larger and hinder water flow more in the case of larger \( D_2 / D_1 \).

<table>
<thead>
<tr>
<th>( D_2 : D_1 )</th>
<th>( K_{sc} )</th>
<th>( K_{se} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>0.5</td>
<td>0.43</td>
<td>0.56</td>
</tr>
<tr>
<td>0.3</td>
<td>0.49</td>
<td>0.82</td>
</tr>
</tbody>
</table>

But, we can also see that though we can see dependence of change of height's oscillation on the ratio of \( D_2 : D_1 \), it is not large. From these results, it may be thought that effects of only one pair of sudden expansion and sudden contraction in the underground watercourse are not very large.

Then I expand the above extended dynamical model into the case where the other shape, for example, an elbow shape, or repeats of the same shape, for example, repeats of a sudden contraction and expansion, exist in a watercourse.

In the case where repeats of the same shapes exist in a watercourse, we can easily modify the former extended dynamic model by taking the effects of these repeats into consideration. For example, in the case where repeat pairs of sudden contractions and expansions exist in a watercourse, the extended dynamic model is modified as follows.
In the case of $\frac{dx}{dt} \geq 0$

$$(n_0 + \beta t)(V_0 + Sx) \rho H \frac{d^3x}{dt^3} + (n_0 + \beta t)(V_0 + Sx) \rho m K \omega \frac{dx}{dt} \frac{d^2x}{dt^2} + (n_0 + \beta t) \rho S \frac{dx}{dt} = (V_0 + Sx) \rho \beta$$

(3.34)

In the case of $\frac{dx}{dt} \leq 0$

$$(n_0 + \beta t)(V_0 + Sx) \rho H \frac{d^2x}{dt^2} + (n_0 + \beta t)(V_0 + Sx) \rho m K \omega \left( \frac{D_2}{D_1} \right) \frac{dx}{dt} \frac{d^2x}{dt^2} + (n_0 + \beta t) \rho S \frac{dx}{dt} = (V_0 + Sx) \rho \beta$$

(3.35)

where $m$ represents the number of repeats of pairs of sudden contractions and expansions. Equations (3.34) and (3.35) are basic equations that include these effects.

Next I show the results of numerical simulation in the case where repeat pairs of sudden contractions and expansions exist in a watercourse. Adopted values of parameters are the same as stated above. And I adopt 0.7 as the value of $D_2 : D_1$.

Temporal variation of a top of a water pole depends on the number of pairs of sudden expansions and contractions as shown in Fig 3.15. We can see from Fig 3.15 that the larger the number of sudden expansions and contractions is, the smaller the amplitude of the height’s oscillation is. This is because the resistance due to pairs of sudden expansions and contractions increases in proportion to an increase in their number.

We can also observe that the larger the number of pairs of sudden expansions and contractions, the larger the degree of transformation of the temporal variation graph. That is, the time-variation of the amplitude of the height’s oscillation and so on do not always regularly change due to the number of pairs of sudden expansions and contractions. This may be the key to understanding the spouting mechanism of an irregularly spouting geyser.

As a result, though in the case of only one pair of sudden expansions and
contractions, the effects are not very large as mentioned above, in the case of many of these pairs or complicated shapes in the underground watercourse, the effects are not negligible.

Next, when the other shape exists in a watercourse, we can easily modify the extended dynamic model, taking the effects of the shape into consideration. For example, we consider an elbow shape in a watercourse, as illustrated in Fig 3.16. The arrow shows the flow, which is turned at the region resembling a human elbow.

The loss water head of elbow \( h_b \) is written using loss coefficient of elbow \( K_b \) as:

\[
h_b = K_b \frac{V_i^2}{2g}
\]  (3.36)

where \( V_i \) represents velocity of a flow. And loss coefficient of elbow \( K_b \) is experimentally written using an angle \( \theta \) of the elbow as:

\[
K_b = 0.946 \sin \frac{\theta}{2} + 2.05 \sin^4 \frac{\theta}{2}
\]  (3.37)

Thus, in the case where an elbow shape exists in a watercourse, the extended dynamic model is modified as follows.

(1) In the case of \( \frac{dx}{dt} \geq 0 \)

\[
(n_o + \beta t)(V_o + Sx)\rho H \frac{d^3 x}{dt^3} + (n_o + \beta t)(V_o + Sx)\rho K_b \frac{dx}{dt} \frac{d^2 x}{dt^2} + (n_o + \beta t)S \frac{dx}{dt} = (V_o + Sx) p \beta
\]  (3.38)

(2) In the case of \( \frac{dx}{dt} \leq 0 \)

\[
(n_o + \beta t)(V_o + Sx)\rho H \frac{d^3 x}{dt^3} + (n_o + \beta t)(V_o + Sx)\rho K_b \frac{dx}{dt} \frac{d^2 x}{dt^2} + (n_o + \beta t)S \frac{dx}{dt} = (V_o + Sx) p \beta
\]  (3.39)

Equations (3.38) and (3.39) are basic equations that include the effects of an elbow shape.
Next I present the results of numerical simulation in the case where an elbow shape exists in a watercourse. Adopted values of parameters are the same as stated above. Here the temporal variation of the top of a water pole depending on the angle of elbow is shown in Fig 3.17. We can see from Fig 3.17 that the larger the angle of elbow, the smaller the amplitude of the height’s oscillation because the larger the angle of elbow, the larger the value of $K_b$. That is, the resistance due to an elbow shape increases in obedience to equation (3.37) according to the increase in the elbow's angle.

We can also see that the larger the angle of elbow, the larger the degree of transformation in the temporal variation graph. Moreover, the degree of transformation in the temporal variation graph is very large in the case where the angle of elbow is sufficiently large. As a result, we can see that where there is a large angle elbow in an underground watercourse, the effects of this elbow are not negligible.

In conclusion, I modified the former extended dynamical model taking effects of an elbow shape or repeats of the same shapes, concretely repeats of pairs of sudden expansion and sudden contraction in a watercourse during spouting into consideration and estimate effects of them to spouting dynamics through numerical simulations. Through comparing results of numerical simulations in the case that an elbow shape or repeats of pairs of sudden expansion and sudden contraction exists in a watercourse with those in the case that only one pair of sudden expansion and sudden contraction exists there, we see that a large number of repeats of pairs of sudden expansion and sudden contraction or large angle's elbow in the underground watercourse affect spouting dynamics of a geyser induced by the inflow of gas greatly. Through this study, we can conjecture that shapes having large loss water head and repeats of them in an underground watercourse generally affect spouting dynamics of a geyser greatly.
3.5 Application of the dynamical model to a real geyser induced by the inflow of gas

We can estimate the values of underground parameters through comparing spouting dynamics of real geyser induced by the inflow of gas with that of numerical simulation of the dynamical model. Concretely we select values of underground parameters as spouting dynamics of numerical simulation of the dynamical model fits that of real geyser induced by the inflow of gas, that is, as a spouting period, amplitude of a water pole's oscillation and so on of the numerical simulation fit those of real geyser when we do numerical simulation of the dynamical model. It is thought that the selected values of underground parameters are close to those of the real geyser induced by the inflow of gas.

A sample of comparison between numerical simulation of equation (3.25) and observation of Hirogawara geyser (Yamagata, Japan) is shown in Fig. 3.18. A graph of numerical simulation of equation (3.25) is drawn in comparison with graphs of observational results of Hirogawara geyser in Fig. 3.18. We are able to guess underground parameters which we cannot measure easily because of geological difficulties through comparing results of numerical simulation with those of observation. Concretely we try to fit data of numerical simulation to those of observation changing values of parameters. When both data fit most, we can guess chosen values of parameters are ones of real underground parameters. Estimated values of parameters through the above procedure are shown in Table 3.3.
Table 3.3 Estimated values of parameters through comparing results of numerical simulation with those of observation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_k$</td>
<td>$1.0 \times 10^1 \text{ [N/m}^2]\text{]}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$1.0 \times 10^3 \text{ [kg/m}^3]\text{]}$</td>
</tr>
<tr>
<td>$S$</td>
<td>$1.0 \times 10^{-2} \text{ [m}^2]\text{]}$</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$1.01 \times 10^5 \text{ [N/m}^2]\text{]}$</td>
</tr>
<tr>
<td>$g$</td>
<td>$9.8 \times 10^3 \text{ [kg \cdot m/s}^2]\text{]}$</td>
</tr>
<tr>
<td>$V_0$</td>
<td>$1.4 \times 10^3 \text{ [m}^3]\text{]}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$1.0 \times 10^{-3} \text{ [mol/s]}$</td>
</tr>
<tr>
<td>$R$</td>
<td>$8.31 \times 10^9 \text{ [N \cdot m/K/mol]}$</td>
</tr>
<tr>
<td>$T$</td>
<td>$3.2 \times 10^2 \text{ [K]}$</td>
</tr>
<tr>
<td>$H$</td>
<td>$1.0 \times 10^2 \text{ [m]}$</td>
</tr>
</tbody>
</table>
A spouting exit

A lump of water (a water pole)

A space where gas is supplied at constant rate

Supply of gas

Fig 3.1 An illustration of a geyser induced by inflow of gas

Fig 3.2 Dependence of variation of height of a water pole \( x \) on length (height) of a water pole \( H \) during spouting
Fig 3.3 Dependence of variation of height of a water pole \((x)\) on length (height) of a water pole \((H)\) before spouting.

Fig 3.4 Dependence of variation of height of a water pole \((x)\) on spouting.
Fig 3.5 Dependence of variation of height of a water pole ($x$) on pressure due to surface tension on the lower interface between water and gas ($f_k$)

Fig 3.6 Dependence of variation of height of a water pole ($x$) on volume of underground space ($V_0$)
Fig 3.7  Difference of variation of height of a water pole \((x)\) from start to 800 second after between in case of friction's existing and in case of no friction

Fig 3.8  Difference of variation of height of a water pole \((x)\) from 900 second after to 1400 second after since start between in case of friction's existing and in case of no friction
Fig. 3.9  A snap shot of beginning of spouting at Kibedani Geyser (Shimane, Japan). We can see spouting hot spring water includes many bubbles of gas.

Fig. 3.10  Temporal variation of a top of a water pole depended on \( a \) (in case gas solution is saturated over 100[m] in depth)

Fig. 3.11  Temporal variation of a top of a water pole depended on the depth in which gas solution saturates
Fig. 3.12  Illustration of sudden contraction

Fig. 3.13  Illustration of sudden expansion

Fig. 3.14  Temporal variation of a top of a water pole depended on the ratio of \( D_2 : D_1 \)
Fig 3.15 Temporal variation of a top of a water pole depended on the number of pairs of sudden expansion and sudden contraction.

Fig 3.16 Illustration of an elbow shape.
Fig 3.17  Temporal variation of a top of a water pole depended on the angle of elbow

Fig 3.18  A graph of numerical simulation of Equation (2) comparison with graphs of observation of a geyser induced by inflow of gas (Hirogawara geyser (Yamagata, Japan))
Chapter 4

The analysis using both the static model and the dynamical model

4.1 An outline of the analysis using both the static model and the dynamical model

As stated Chapter 1, a position of the interface between the lump of water in the hole and atmosphere of geysers induced by the inflow of gas generally varies with time. At one time, the position is located above the ground. We call the period a spouting mode. And at one time, the position is located under the ground. We call the period a pause mode. These 2 modes appear alternately or irregularly in obedience to geysers induced by the inflow of gas. For example, we can see from Fig. 1.1 that height of top of the water pole goes up and down by turns and a spouting mode and a pause mode appear alternately and regularly.

The dynamical model of a geyser induced by the inflow of gas as mentioned in Chapter 3 can re-create dynamics of spouting modes. On the other hand, a pause mode can not be reproduced by the dynamical model. But it can be explained by a static model as mentioned in Chapter 2. Therefore a chain of spouting dynamics of a geyser induced by the inflow of gas can be expressed completely using both the static model and the dynamical model. In this analysis using both models the static model or the dynamical model can have independent parameters respectively. From this characteristics, if a value of a parameter of one model, which is decided as results of numerical simulation agrees with those of observation, is different from one of the other model, the value is regarded as unrealistic one. Therefore concerning common parameters to both models equal value has to be had in each model. In this sense, this analysis using both models
can be considered to connote a role as the verification of estimated values of parameters.

In this section, I introduce this analysis using both models and report estimation of parameters under Kibedani geyser based on comparison between results of simulation of both models and those of observation of Kibedani geyser.

In the beginning, using equations in Chapter 2, as the result of the static model of a geyser induced by the inflow of gas we can write a spouting period $T_p$ as:

$$T_p = \left( \frac{V_0}{\alpha \beta} + \frac{f_k S}{\rho g \alpha \beta} \right) \left( f_k + P_0 + \rho g H \right)$$

(4.1)

And as mentioned in Chapter 3, as the result of the dynamical model of a geyser induced by the inflow of gas an evolution equation of temporal variations of height of top of a water pole packed in the spouting pipe of a periodic bubbling spring is written as:

(1) In case of no friction between the wall’s surface along the edge of the paths of water and water

$$\left( n_0 + \beta t \right) (V_0 + Sx) \rho H \frac{d^3x}{dt^3} + \left( n_0 + \beta t \right) pS \frac{dx}{dt} = (V_0 + Sx) p\beta$$

(4.2)

(2) In case friction between the wall’s surface along the edge of the paths of water and water exists

$$\left( n_0 + \beta t \right) (V_0 + Sx) \rho H \frac{d^3x}{dt^3} + \frac{8 \pi \eta H}{S} \left( n_0 + \beta t \right) (V_0 + Sx) \frac{d^2x}{dt^2} + \left( n_0 + \beta t \right) pS \frac{dx}{dt} = (V_0 + Sx) p\beta$$

(4.3)

The analysis consists of the static model and the dynamical model of a periodic bubbling spring. Concretely, temporal variations of height of top of the water pole of a periodic bubbling spring as shown Fig. 1.1 is dealt with by the dynamical model. And a spouting period, that is, time from a beginning of a pause mode to next one is dealt with by the static model.
4.2 Results of numerical simulation using both the static model and the dynamical model and discussion

The analysis using both models is first applied to Kibedani geyser because in the case of it pause modes and spouting modes appear alternately and almost regularly. The results of observation of Kibedani geyser shown in Fig. 1.1 were used as comparison with the combined model.

From the results of observation of Kibedani geyser we can see a spouting period is almost 30 minutes. So at first each parameter has to be decided as a spouting period $T_p = 30[\text{min}]$ using equation (4.1). Moreover, each parameter also has to be decided as temporal variations of height of top of a water pole of Kibedani geyser are reproduced by numerical simulations using equation (4.3).

A graph of temporal variations of height of top of a water pole obtained based on above procedure is shown in Fig. 4.1. Results of two kinds of numerical simulations, that is, a result of the dynamical model and that of the analysis using both models are shown for comparison in Fig. 4.1. And parameters used by this simulation of the analysis using both models are as follows:

$S = 0.01[\text{m}^2], \ T (\text{temperature of gas in the underground space}) = 320[\text{K}], \ H = 100[\text{m}], \ f_r = 22[\text{N/m}^2], \ \nu = 990[\text{m}^3], \ \beta = 0.00019[\text{mol/s}]$

Above the result of simulation is a sample. Possibly another set of parameters may bring about more suitable results of simulation. An essential point is that we can estimate more reliable parameters using the analysis using both models.

In conclusion, I introduced the analysis using both the static model and the dynamical model of a geyser induced by the inflow of gas and reported the estimation of parameters under Kibedani geyser based on comparison between results of simulation
of this analysis using both models and those of observation of Kibedani geyser.

In case of using only the modified dynamical model, we can select many groups of parameters suitable for results of observation. But, in case of using the analysis using both models, the number of groups of parameters suitable for results of observation is strictly limited because of demands from 2 independent models, that is, the static model and the dynamical model. In this sense, the estimation of parameters through the analysis using both models makes more reliable one.
Fig 4.1 Temporal variation of top of a water pole of Kibedani geyser (Observation, Simulations (Dynamical model, The analysis using both models))
Chapter 5

Verification of the models of a geyser induced by the inflow of gas by underground investigation of Kibedani geyser

5.1 Results of various underground investigation

Though above models are compared with observation of real geyser, the observation of geysers has been limited only to dynamics of their spouting because of difficulty of underground observation. For example, when we use metal (conductive) factor which is one effective method for watching underground geological features, in case of watching one over 100 [m] in depth large-scale equipment is needed and accuracy is not enough. However, it is desirable that underground observation of geysers will be also done for verification. So we try indirect observational verification through geological exploration, the analysis of hot spring water and radioactive prospecting.

I selected Kibedani Geyser (geyser induced by the inflow of gas) as observation points. Kibedani Geyser is located at Shimane prefecture in Japan. An appearance of Kibedani Geyser is shown in Fig 5.1. It has regular spouting period (about 25 minutes).

Observation points were selected within the limits of about 2km in diameter around it shown in Fig 5.2. That is, many representative spots were selected from the range shown as a circle in Fig 5.2.

According to a wide range of past geological plan near Kibedani Geyser, there are some dislocations of about NW – SE direction around it. But Kibedani Geyser is located near the end of a dislocation of about NW – SE direction and the existence of the dislocation has not been confirmed yet. Then we tried to confirm the existence of
dislocations through geological exploration, too.

Geological exploration was done on 30, 31 March 2006. It was rainy on 30 and clear on 31.

A geological plan near Kibedani Geyser obtained through geological exploration is shown in Fig 5.3. A dotted line in Fig 5.3 shows a presumed dislocation in a past geological plan and straight lines in Fig 5.3 show observed dislocations in this geological exploration. That is, some dislocations of about NW – SE direction which was a different direction from one presumed in a past geological plan were found near Kibedani Geyser. But this is peculiar to the edge of another intersecting dislocation. It is imagined that hot spring water gushes along dislocations of the same direction as observed one. Indeed, the gushing points of hot spring water were found at about 20[m] away from a spouting hole of Kibedani Geyser in the direction of SE (Fig 5.5) and about 50[m] away from a spouting hole in the direction of North (Fig 5.6).

And a presumed geological cross section near Kibedani geyser in cutting along the cross section line shown in Fig 5.3 is shown in Fig 5.4. The grounds are explained below. In the beginning, rocks found typically around here are granite, granodiorite and so on. Typical rocks found around here are shown in Fig 5.7. And talus deposit made of mainly granite is distributed near a mountain stream or gentle talus of the skirts of a mountain around Kibedani Geyser. Typical talus deposit found around here are shown in Fig 5.8.

Next we analyze hot spring water of Kibedani Geyser. Ingredients of hot spring water gushing from Kibedani Geyser have already been clarified and shown on a sign board in front of Kibedani Geyser. Then we tried to clarify the origin of the hot spring water using the data of ingredients of hot spring water through trilinear diagram.

Trilinear diagram made from the data of ingredients of hot spring water of
Kibedani Geyser is shown in Fig 5.9. In the case of Kibedani geyser, the length of water stay is long. That is, the water originates in an underground deep spot.

5.2 Estimated underground caves and their forming mechanism

In this section, I discuss above results of various underground investigation.

In the beginning, it is suggested that hot spring water gushes through cracks of dislocations.

Then, is there an underground cave (space)? We can list below 3 possibilities.

(a) gaps in cracks of granite
(b) druse formed in granite
(c) gaps among pebbles and sand in talus deposit

But, in case of (a) gaps in cracks of granite, estimated volume is too small. And druse is rarely formed in granite. As a result, in case of (b) druse formed in granite, imaged volume is small compared with one assumed by the model. In case of (c) gaps among pebbles and sand in talus deposit, it is thought that total volume of gaps reaches as large as one estimated by the model. Finally, “(c) gaps among pebbles and sand in talus deposit” is most possible idea.

Based on above idea, we propose a scenario of underground cave’s formation below. It is thought that underground caves were formed obeying sequence illustrated in Fig 5.10. That is, it is thought that interaction of tales deposit and deposit of hot spring water formed large volume of underground gaps.

In conclusion, it is suggested that underground caves (spaces) which are needed by the model can exist by summing gaps among pebbles and sand in talus deposit as results of indirect geological exploration at Kibedani geyser. And it is suggested that hot
spring water gushes through dislocations from an underground deep spot. Finally, it is thought that the combined model is indirectly verified. But we have to continue geological investigation further at Kibedani geyser to verify the model correctly.
Fig 5.1 An appearance of Kibedani Geyser.
Fig 5.2 Observation spots were selected from the range shown as a circle. A diameter of the circle is about 2 km.
Kibedani Geyser

A line of the cross section shown in Fig 6.4

Fig 5.3  A geological plan near Kibedani Geyser obtained through geological exploration

Fig 5.4  A presumed geological cross section near Kibedani geyser

Legend
tr : terrace deposit
dt : talus deposit
VoO : Dacite pyroclastic rock
Fig 5.5 Gushing point of hot spring water found at about 20[m] away from a spouting hole of Kibedani Geyser in the direction of SE
Fig 5.6  Gushing point of hot spring water found at about 50[m] away from a spouting hole of Kibedani Geyser in the direction of North
Fig 5.7  Typical granite found near exploration points
Fig 5.8  Typical talus deposit found near exploration points
Fig 5.9 Trilinear diagram made from the data of ingredients of hot spring water of Kibedani Geyser
Before piling up of talus deposit

After piling up of talus deposit

Repeats of piling up of talus deposit and deposit

*Hot spring water gushes through a crack of a dislocation*

**Fig 5.10** An illustrated scenario of underground cave's formation around Kibedani Geyser
Chapter 6

Development of the dynamical model of a geyser induced by the inflow of gas

6.1 An improved dynamical model in which two underground gas supply sources are assumed

Concerning a geyser induced by the inflow of gas, there are not only one spouting regularly but also one spouting irregularly. For example, Hirogawara Geyser (Yamagata, Japan) is an instance of a geyser induced by the inflow of gas spouting irregularly. In case of a geyser induced by the inflow of gas spouting irregularly we cannot explain its spouting mechanism based on above-mentioned usual dynamical model which assumes single underground gas supply source. In such a case it is natural that we think there are plural underground gas supply sources and interaction of them produces irregular spouting period.

In this study, I propose a dynamical model which assumes plural underground gas supply sources by extension of above-mentioned usual dynamical model. Then I show complicated spouting period occurs as a result of interaction of plural underground gas supply sources through numerical simulation of this extended dynamical model. I aim at clarification of spouting mechanism of a geyser induced by the inflow of gas spouting irregularly through this study.

In the beginning, I suppose simple underground system having two underground gas supply sources as shown in Fig 6.1. There is a water pole on each gas supply source. The upper surface of the water is common to both water poles. A central dotted line in Fig 6.1 shows that 2 water poles are separated under the ground. Each water pole
moves almost independently except for interaction at the upper surface of the water. Now we define x-, y- and z-axis as upward vertical direction and set the origin of x-, y- and z-axis at the lower surface of the right water pole, one of the left water pole and the upper surface of the water, respectively. And we name the right watercourse and the left one for watercourse A and watercourse B, respectively.

Then a basic dynamical equation of each watercourse (A, B) based on the former model is written as:

\[
(n_{0A} + \beta_A t)(V_{0A} + S_A x)p(z - x)\frac{d^3x}{dt^3} + (n_{0A} + \beta_A t)p_A S_A \frac{dx}{dt} = (V_{0A} + S_A x)p_A \beta_A
\]  

(6.1)

\[
(n_{0B} + \beta_B t)(V_{0B} + S_B y)p(z - y)\frac{d^3y}{dt^3} + (n_{0B} + \beta_B t)p_B S_B \frac{dy}{dt} = (V_{0B} + S_B y)p_B \beta_B
\]  

(6.2)

where \( n_{0A} \) or \( n_{0B} \) represents molar number of gas in a underground space just before the water pole's beginning to move up, \( \beta_A \) or \( \beta_B \) is constant concerning gas supply rate, \( V_{0A} \) or \( V_{0B} \) represents volume of gas packed in a underground cave, \( S_A \) or \( S_B \) represents an area of a cross section of the spouting pipe and \( p_A \) or \( p_B \) represents the pressure of gas packed in the underground cave in watercourse A or B, respectively.

And an equation concerning conservation of water volume is written as:

\[
S_A(z - x) + S_B(z - y) = S_A H_A + S_B H_B
\]  

(6.3)

where \( H_A \) or \( H_B \) represents the initial height of a water pole of watercourse A or one of watercourse B, respectively.

Then I show some results of numerical simulation of the above extended dynamical model and discuss them.

In the beginning, I show dependence of variation of height of a water pole on cross section of one side's watercourse \((S_A)\) in case of one of the other side's watercourse \((S_B)\) = \(1.1 \times 10^2[\text{m}^2]\) in Fig 6.2. The other parameters are set as follows: \( H_a = H_b = 9.1 \times \)
10^4[m], \( V_a = V_b = 4.0 \times 10^2[m^2] \), \( \beta_a = \beta_b = 1.9 \times 10^{-4}[\text{mol/s}] \). We may see that irregular spouting dynamics is realized. And we see that the larger difference between cross section of one side’s watercourse (\( S_a \)) and one of the other side’s watercourse (\( S_b \)) is, the smaller an amplitude of temporal variation of water pole’s height is and the shorter an irregular period of it is. These characteristics appear for the reason that when cross section of the other side’s watercourse is larger, volume of water pushed up due to pressure of gas packed in an underground cave is absorbed more not by the height but by the cross section. This effect brings about control of a rise of the height of a water pole and early arrival at the maximum point of it. Therefore, when cross section of the other side’s watercourse is larger, the amplitude of temporal variation of water pole’s height is smaller and the irregular period of it is shorter.

Then I show the dependence of variation of height of a water pole on volume of one side’s underground cave (\( V_a \)) in case of the other side’s underground cave (\( V_b = 4.0 \times 10^2[m^3] \)) in Fig 6.3. The other parameters are set equivalent to the above. We also see that irregular spouting dynamics is realized. And we see that the larger difference between volume of one side’s underground cave (\( V_a \)) and one of the other side’s underground cave (\( V_b \)) is, the smaller degree of irregularity of temporal variation of water pole’s height is because the cave whose volume is larger than the other controls whole temporal variation of water pole’s height more. And the larger volume of one side’s underground cave (\( V_a \)) is, the larger the amplitude of temporal variation of water pole’s height is and the longer the irregular period of it is. The reason of this is the same one seen in case of the former dynamical model in which a single underground gas supply source is assumed. That is, when the volume of an underground cave is larger, power due to the pressure of gas packed in an underground cave, which pushes up
water packed in the spouting pipe, is larger. Therefore, when the volume of an underground cave is larger, water packed in the spouting pipe is pushed up higher and longer due to pressure of gas packed in an underground cave and as a result the amplitude of temporal variation of water pole's height is larger and the irregular period of it is longer.

Then I show dependence of variation of height of a water pole on depth of one side's gas supply source \((H_a)\) in case of one of the other side's gas supply source \((H_b) = 9.1 \times 10^1\) [m] in Fig 6.4. We may see that in case of dependence of variation of height of a water pole, irregular spouting dynamics is realized concerning not spouting period but amplitude of oscillation of height of a water pole. We can see that when difference between the depth of one side's gas supply source and one of the other is enough small, amplitude of oscillation of height of a water pole does not change, and when the difference is enough large, the amplitude gradually decreases. These characteristics originate from whether “pseudo-synchronization” occurs in the system. For example, “pseudo-synchronization” occurs in the case of \(H_a = 1.8 \times 10^2\) [m] in Fig 6.4. In this case, an oscillation period of the water pole packed in watercourse A is a little longer than that in watercourse B. Therefore, as time goes by, it seems that synchronization occurs in the system. But this is not complete synchronization. After the amplitude of oscillation of height of a water pole decreases as time passes, it increases again as time passes. For an independent oscillation of each watercourse is maintained in spite of the common upper surface between the atmosphere and water packed in the pipes (Fig 6.1). By the way, in case there is single underground gas supply source, when height of a water pole is higher, amplitude of oscillation of height of a water pole is larger and a spouting period is a little longer.
Lastly, I show dependence of variation of height of a water pole on one side's gas supply rate \( \beta_a \) in case of the other side's gas supply rate \( \beta_b \) = \( 1.9 \times 10^{-4} \) [mol/s] in Fig 6.5 for reference. We can see that difference of one side's gas supply rate does not affect both amplitude of oscillation of height of a water pole and a spouting period. For a gas supply rate affects only average rising rate of height of a water pole.

In conclusion, I derived a dynamical model of a geyser induced by the inflow of gas in case of having two underground gas supply sources based on the former dynamical model in case of having one underground gas supply source. Irregular spouting dynamics was realized through numerical simulation of the dynamical model. And dependence of spouting dynamics of the model on various parameters was clarified. And each parameter's effect which brings about irregular spouting was clarified. This will make it possible to estimate various underground parameters of geysers induced by the inflow of gas spouting irregularly more exactly [Kagami, 2010] [Kagami, 2011].

6.2 An improved dynamical model - 5 in which three underground gas supply sources are assumed

We can easily extend the above-mentioned model having two underground gas supply sources to one having three underground gas supply sources. An assumed system in case of having three underground gas supply sources is shown in Fig 6.6. There is a water pole on each gas supply source. The upper surface of the water is common to all water poles. Dotted lines in Fig 6.6 show that 3 water poles are separated under the ground. Each water pole moves almost independently except for interaction at the upper surface of the water. Now we define x-, y-, w- and z-axis as upward vertical direction and set the origin of x-, y-, w- and z-axis at the lower surface of the right water
pole, one of the left water pole, one of the central water pole and the upper surface of the water, respectively. And we name the right watercourse, the left one and the center one for watercourse A, watercourse B and watercourse C, respectively.

Then a basic dynamical equation of each watercourse (A, B, C) based on the former model is written as:

\[
(n_{0A} + \beta_A t) (V_{0A} + S_A x) \rho (z - x) \frac{dx}{dt} + (n_{0A} + \beta_A t) p_A S_A \frac{dx}{dt} = (V_{0A} + S_A x) p_A \beta_A \tag{6.1}
\]

\[
(n_{0B} + \beta_B t) (V_{0B} + S_B y) \rho (z - y) \frac{dy}{dt} + (n_{0B} + \beta_B t) p_B S_B \frac{dy}{dt} = (V_{0B} + S_B y) p_B \beta_B \tag{6.2}
\]

\[
(n_{0C} + \beta_C t) (V_{0C} + S_C w) \rho (z - w) \frac{dw}{dt} + (n_{0C} + \beta_C t) p_C S_C \frac{dw}{dt} = (V_{0C} + S_C w) p_C \beta_C \tag{6.3}
\]

where \( n_{0A}, n_{0B} \) or \( n_{0C} \) represents molar number of gas in a underground space just before the water pole’s beginning to move up, \( \beta_A, \beta_B \) or \( \beta_C \) is constant concerning gas supply rate, \( V_{0A}, V_{0B} \) or \( V_{0C} \) represents volume of gas packed in a underground cave, \( S_A, S_B \) or \( S_C \) represents an area of a cross section of the spouting pipe and \( p_A, p_B \) or \( p_C \) represents pressure of gas packed in the underground cave in watercourse A, B or C, respectively.

And an equation concerning conservation of water volume is written as:

\[
S_A (z - x) + S_B (z - y) + S_C (z - w) = S_A H_A + S_B H_B + S_C H_C \tag{6.4}
\]

where \( H_A, H_B \) or \( H_C \) represents initial height of a water pole of watercourse A, one of watercourse B or one of watercourse C, respectively.

Then I show some results of numerical simulation of the above extended dynamical model and discuss them.

In the beginning, I show temporal variation of height of a water pole in case of having three underground gas supply sources compared with that in case of having two
underground gas supply sources in Fig 6.7. Then I show dependence of variation of height of a water pole on cross section of watercourse A \( S_A \) in case of cross section of watercourse B \( S_B \) = 1.1 \times 10^{-2}[m^2] and that of watercourse C \( S_C \) = 5.0 \times 10^{-3}[m^2] in Fig 6.8.

From these figures, we see that “third” gas supply source affects spouting dynamics and its complexity increases a little. And we also see that “third” gas supply source functions as if there is one gas supply source having parameters which average parameters of “second” gas supply source and those of “third” gas supply source [Kagami, 2012].

6.3 Application of the improved dynamical model to a real geyser induced by the inflow of gas spouting irregularly

Real spouting dynamics of a geyser induced by the inflow of gas spouting irregularly should be reproduced through numerical simulation of this model. Then as a result, various underground parameters should be estimated.

In the present study, I apply the above-mentioned three-source dynamical model to an actual irregularly spouting geyser induced by gas inflow. Specifically, the results of numerical simulations based on this model were compared with data obtained from observations of an actual irregularly spouting geyser induced by gas inflow in order to estimate the relevant parameters. The results demonstrate that the parameters of the underground configuration for such irregularly spouting geysers can be estimated from their spouting dynamics.

The results of a numerical simulation based on the three-source dynamical model are compared with observation data for an irregularly spouting geyser induced by gas
inflow. Specifically, each parameter of the model is chosen by considering the spouting dynamics based on a numerical simulation where the model agrees with that based on observation data for an irregularly spouting geyser induced by gas inflow as closely as possible. The method of estimating the parameters is as follows. First, a numerical simulation is conducted under any set of parameters, after which the degree of fitness of the set of parameters is estimated by comparing the results of numerical simulation with the observation data. Therefore, multiple numerical simulations are conducted by gradually changing the values of the parameters. Finally, the set of parameters for which the result of the numerical simulation produces the closest fit to the observation data is evaluated as the most appropriate set of parameters. Observation data for the Hirogawara Geyser are used as data for an irregularly spouting geyser induced by gas inflow. Through this process, we can estimate the actual parameters of the underground configuration of an irregularly spouting geyser induced by gas inflow.

A comparison of the results of numerical simulations based on the three-source dynamical model with observation data for an irregularly spouting geyser induced by gas inflow is shown in Fig. 6.9. The parameters for the underground configuration as

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_A )</td>
<td>80 [m]</td>
</tr>
<tr>
<td>( H_B )</td>
<td>100 [m]</td>
</tr>
<tr>
<td>( H_C )</td>
<td>110 [m]</td>
</tr>
<tr>
<td>( S_A )</td>
<td>0.0012 [m(^2)]</td>
</tr>
<tr>
<td>( S_B )</td>
<td>0.0020 [m(^2)]</td>
</tr>
<tr>
<td>( S_C )</td>
<td>0.0051 [m(^2)]</td>
</tr>
<tr>
<td>( V_A )</td>
<td>240 [m(^3)]</td>
</tr>
<tr>
<td>( V_B )</td>
<td>200 [m(^3)]</td>
</tr>
<tr>
<td>( \beta_A )</td>
<td>0.00019 [mol/s]</td>
</tr>
<tr>
<td>( \beta_B )</td>
<td>0.00019 [mol/s]</td>
</tr>
<tr>
<td>( \beta_C )</td>
<td>0.00019 [mol/s]</td>
</tr>
<tr>
<td>( f_{ia} )</td>
<td>42 [N/m(^2)]</td>
</tr>
<tr>
<td>( f_{ic} )</td>
<td>22 [N/m(^2)]</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>320 [K]</td>
</tr>
</tbody>
</table>

Table 6.1 Estimated underground parameters through comparison of results of numerical simulation of the further extended dynamical model with observation of irregularly spouting geyser induced by the inflow of gas
estimated through this comparison are listed in Table 6.1. Here, \( f_{kA} \), \( f_{kB} \) and \( f_{kC} \) represent pressure due to surface tension at the interface between water in the spouting pipe and gas in the underground cave for watercourses A, B and C, respectively.

Through the above procedure, we can estimate the parameters of the underground configuration of an irregularly spouting geyser induced by gas inflow.

As a result, the parameters of the underground configuration for an irregularly spouting geyser induced by inflow of gas of can be estimated in the particular case of the Hirogawara Geyser through comparison of the results of numerical simulation based on the three-source dynamical model with observation data for Hirogawara Geyser. The parameters of an irregularly spouting geyser induced by gas inflow are considered, in general, to be estimable by this method [Kagami, 2012].
Fig 6.1 An assumed system of an extended dynamical model which assumes two underground gas supply sources.
Fig 6.2  Dependence of variation of height of a water pole on cross section of one side's watercourse \((S_A)\) in case of one of the other side's watercourse \((S_B) = 1.1 \times 10^{-2}\)\(\text{m}^2\)

![Graph showing variation of height of a water pole with cross section]

Fig 6.3  Dependence of variation of height of a water pole on volume of one side's underground cave \((V_a)\) in case of the other side's underground cave \((V_b) = 4.0 \times 10^2\)\(\text{m}^3\)

![Graph showing variation of height of a water pole with volume]
Fig 6.4  Dependence of variation of height of a water pole on depth of one side's gas supply source ($H_A$) in case of one of the other side's gas supply source ($H_B$) = 9.1 × 10^1 [m]

Fig 6.5  Dependence of variation of height of a water pole on one side's gas supply rate ($\beta_a$) in case of the other side's gas supply rate ($\beta_o$) = 1.9 × 10^4 [mol/s]
Fig 6.6  An assumed system of an extended dynamical model which assumes three underground gas supply sources

Fig 6.7  A sample of dependence of variation of height of a water pole on the number of underground gas sources concerning cross section of watercource ($S_A = 2.5 \times 10^{-2}$[m$^2$], $S_B = 1.1 \times 10^{-2}$[m$^2$] and $S_C = 5.0 \times 10^{-1}$[m$^2$])(only in case of 3 underground gas sources)
Fig 6.8 Dependence of variation of height of a water pole on cross section of watercourse A ($S_A$) in case of cross section of watercourse B ($S_B$) = $1.1 \times 10^{-2}$[m$^2$] and that of watercourse C ($S_C$) = $5.0 \times 10^{-3}$[m$^2$]

Fig 6.9 A sample of comparison of results of numerical simulation of the further extended dynamical model with observation of irregularly spouting geyser induced by the inflow of gas
Chapter 7

Summary

1. I constructed a static model of a geyser induced by inflow of gas through detailed observation of the indoor model experiments. And I confirmed that results of analysis of the model agreed those of the indoor model experiments.

2. I constructed a basic dynamical model of a geyser induced by inflow of gas through detailed observation of the indoor model experiments. And I clarified dependence of spouting dynamics on various underground parameters (volume of the underground space, depth of spouting hole and so on) through numerical simulation of the dynamical model.

3. I improved the dynamical model, that is, I took effects of friction between the walls of the spouting pipe and water into account. And I clarified how spouting height was damped by friction between the walls of the spouting pipe and water through numerical simulation of the improved dynamical model.

4. I improved the dynamical model furthermore, that is, I add evaporation effect of gas dissolved in hot spring water during spouting to the dynamical model so as to re-create more practical spouting of a geyser induced by inflow of gas. And we saw slope of the graph of a top of water pole's temporal variation under 0[m] (the surface of the earth) is steeper than one over 0[m] through numerical simulation of the further improved dynamical model. That is characteristic for real spouting of a periodic bubbling spring. And through numerical simulation of the model we also see that the deeper saturated depth is, the steeper slope of the graph under 0[m] is.
5. I improved the dynamical model furthermore. Concretely, I added effects of a complicated underground watercourse and their repeats during spouting to the dynamical model. As a result, we see that though in the case of only one pair of sudden expansions and contractions, the effects are not very large, in the case of many of these pairs or complicated shapes in the underground watercourse, the effects are not negligible. And we also see that the larger the angle of elbow, the larger the degree of transformation in the graph of a top of water pole’s temporal variation.

6. I showed we could estimate values of underground parameters through comparing spouting dynamics of real geyser induced by inflow of gas with that of numerical simulation of the dynamical model. As a sample, comparison between numerical simulation of the model and observation of Hirogawara geyser (Yamagata, Japan) was shown.

7. I constructed a combined model of a geyser induced by inflow of gas combining the static model and the dynamical model. The estimation of underground parameters through the combined model make more reliable one because of demands from 2 independent models, that is, the static model and the dynamical model.

8. I verified the models of a geyser induced by inflow of gas by underground investigation of Kibedani geyser. In conclusion, it is suggested that underground caves (spaces) which are needed by the model can exist by summing gaps among pebbles and sand in talus deposit as results of indirect geological exploration at Kibedani geyser. And it is suggested that hot spring water gushes through dislocations from an underground deep spot. Finally, it is thought that the combined model is indirectly verified.
9. I developed the dynamical model. Concretely, I proposed a dynamical model which assumed plural underground gas supply sources by extension of above-mentioned usual dynamical model so as to re-create spouting dynamics of a geyser induced by inflow of gas spouting regularly. As a result, Irregular spouting dynamics was realized through numerical simulation of the dynamical model. And dependence of spouting dynamics of the model on various parameters and each parameter's effect which brings about irregular spouting were clarified.

10. I applied the above-mentioned three-source dynamical model to an actual irregularly spouting geyser induced by gas inflow. Specifically, the results of numerical simulations based on this model were compared with data obtained from observations of an actual irregularly spouting geyser induced by gas inflow in order to estimate the relevant parameters. The results demonstrate that the parameters of the underground configuration for such irregularly spouting geysers can be estimated from their spouting dynamics.
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(1) Explanations of spouting dynamics of a geyser (periodic bubbling spring) and estimation of parameters under it based on a combined model combining the mathematical model (a static model) and the improved dynamical model of one, Kagami, H., Edited by Namsik Park, *Advances in Geosciences, Vol. 4*, 191～197, Copyright @2006, World Scientific Publishing Co Pte Ltd, doi: 10.1142/9789812707208_0024.


(4) An extended dynamical model of a geyser induced by inflow of gas : considering


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References


Ishii, E., (1999). Kagami found that water packed in the pipe as a watercourse leading to a spouting exit does not spout as soon as the position of the interface between gas and water in the flask goes down under one of the lower entrance of the left pipe due to a surface tension on an interface
between water and gas in the lower entrance of the pipe as the watercourse when Ishii did the indoor model experiments in front of Kagami.


List of publications

1. Kagami, H., Explanations of spouting dynamics of a geyser (periodic bubbling spring) and estimation of parameters under it based on a combined model combining the mathematical model (a static model) and the improved dynamical model of one, *Advances in Geosciences, Vol. 4*, 191~197, 2006.


This thesis is based on papers 1. – 8..