Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

To request permissions please use the Feedback form on our webpage. [http://researchspace.auckland.ac.nz/feedback](http://researchspace.auckland.ac.nz/feedback)

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form.
Chapter 6

THE DEVELOPMENT OF A FULLY TRANSIENT MODEL OF A GEYSER USING A NUMERICAL APPROACH

In previous chapters two mathematical models for simulating processes within a geyser were presented. The models are easy to use for the sensitivity analysis but they are not entirely satisfactory since they model each phase of a geyser activity separately and do not give a description of the transient development through all these phases. Also they consider the behaviour of the geyser only from the end of one eruption until the beginning of the next. They do not model the eruption process at all. Therefore data on the duration of play cannot be used for model calibration. This chapter discusses the development of a fully transient numerical model of a geyser based on the geothermal reservoir simulators called MULKOM and AUTOUGH2 (Pruess 1983, 1987, 1988, 1991). This model uses a distributed parameter approach to allow for spatial variations in rock and fluid properties. It is hoped that with this approach the model can provide some insight into the behaviour of a geyser system as a whole and give a quantitative measure of the surface discharge which cannot be obtained from the simple mathematical models considered in Chapters 4 and 5.

This chapter consists of four parts. Part one briefly describes the underlying principles incorporated in the simulators. Part two describes the development of a fully transient model of a geyser using MULKOM and AUTOUGH2, based on the conceptual model and data given by Steinberg et al. (1981a), which was previously discussed in Chapter 4. Part three discusses the results of a modelling study using AUTOUGH2 to simulate some of the experiments which were previously discussed in Chapter 3. Part four describes the sensitivity of the Steinberg-like AUTOUGH2 model, developed in part 2, to changes in the permeability, changes in the rate and temperature of the inflow, changes in the pressure and temperature of the cold water zone, changes in the size of the vent and to variations in the atmospheric pressure and ambient temperature.

The work described here is similar to that developed in parallel and independently by Ingebritsen and Rojstaczer (1993). Their model produces oscillatory behaviour within two to three eruption cycles with a fairly constant interval between eruptions (±10%). The conceptual model, the parameters and the initial conditions used, however, are different from those used in the work described here. Their model will be discussed later in this chapter.
6.1. MULKOM and AUTOUGH2

MULKOM is a computer code developed at Lawrence Berkeley Laboratory for simulating non isothermal flow in porous and fractured media, involving water, steam and heat (Pruess 1988). Some improvements to MULKOM, made at the University of Auckland, allow the behaviour of geothermal reservoirs containing large amounts of non-condensible gas, particularly CO₂, and dissolved solids to be simulated (O'Sullivan, 1985).

AUTOUGH2 is the University of Auckland version of TOUGH2 (Pruess, 1991). TOUGH2, which belongs to the MULKOM family of codes, has several options for investigating flows which include extra components as well as air. Of particular interest to the present study is that it can handle a mixture of water, steam and air.

Detailed discussions of the governing equations incorporated in the MULKOM family of codes has been presented in several publications (Blakeley, 1986; Yang, 1991, 1993 for example) and therefore only a brief description is presented here. Both simulators require the region of interest to be divided into a number of blocks or elements to allow for spatial variations in rock and fluid properties. The underlying principles incorporated in all codes belonging to the MULKOM family of codes are conservation of mass, heat and chemicals. The fluid flow is governed by Darcy's law for flow in porous media, which states that the volume flux is proportional to pressure gradient. Relative permeabilities are introduced to describe two-phase flow. The boundary conditions can be specified in terms of either constant pressure and temperature or constant heat and mass fluxes. The code can solve fully transient problems and solves the governing equations using an integrated finite difference method for the pressure and the temperature (or the fluid saturation) in each block, and the mass and heat flow to the connected blocks.

MULKOM has been used for simulating many geothermal systems in New Zealand and elsewhere. Several geothermal systems in New Zealand have been simulated using MULKOM, or modified versions of it, for example: Wairakei (Blakeley and O'Sullivan, 1981, 1985; Blakeley, 1986; Blakeley, Bullivant and O'Sullivan, 1990 as mentioned in Yang, 1993), Broadlands or Ohaaki (Blakeley et al., 1983; Blakeley, 1986), Rotorua (Grant et al, 1985; Burnell, 1992) and Waiotapu (Newson, 1993). Many other geothermal systems have been simulated using MULKOM, for example: Cerro Prieto in Mexico (Lippmann and Bodvarsson, 1983), Krafla in Iceland (Bodvarsson et al., 1982, 1984; Pruess et al., 1984), Olkaria in Kenya (Bodvarsson and Pruess, 1981, 1984 as reviewed in O'Sullivan, 1987), Nesjavellir also in Iceland (Bodvarsson et al., 1990, 1991), Tongonan in the Philippines (Salera, 1987; Salera and O'Sullivan, 1987) and Kamojang in Indonesia (O'Sullivan et al., 1990). All these
studies have shown that MULKOM can satisfactorily model the performance of geothermal reservoirs and provide some insight into important reservoir parameters such as permeability structure, temperature and pressure distributions, and mass and fluid flows within a system.

The use of TOUGH2 for simulations of geothermal systems with unsaturated zones (zones extending from the water table to the ground surface occupied partially by water and partially by air), with some applications to Tongonan, Olkaria and Wairakei geothermal fields, has been studied by Yang (1993). The model for the Olkaria geothermal system was able to reproduce the occurrence of fumarole and acid springs associated with the system and provide some insight into the physical processes occurring inside the system. The model for the Wairakei geothermal system was used to simulate changes in surface manifestations and heat flows as a result of production in the borefield.

There are two limitations of these simulators for modelling a geyser. These are:

(a) The flow is assumed to obey Darcy's law which is valid only for describing the flow processes in porous media. This assumption has been used in all geothermal modelling even though the flows in geothermal systems is mainly through fractures, because Darcy's law is the best available mathematical description of the flow processes (O'Sullivan, 1987). As the chamber and the channel of a geyser may be much larger than typical fractures, this assumption may lead to significant inaccuracies.

(b) Relative permeabilities of various kinds for water and steam in porous media have been used to represent two-phase flow in all geothermal modelling studies and they are used in MULKOM and AUTOUGH2. Reliable data for flow in fractures are not available. Many attempts, however, have been made to deduce relative permeability curves from production data (Horne and Ramey, 1978; Iglesias et al., 1985; Gudmundsson et al., 1986). The inferred relative permeability curves differ from those of Corey (see O'Sullivan and McKibbin, 1988) in that in their curves both liquid and steam phases become immobile only if their saturations are zero \( (S_{LR}=0 \text{ and } S_{VR}=0) \), whereas in the Corey curves the liquid phase becomes immobile when the liquid saturation is 0.3 \( (S_{LR}=0.3) \) and the steam phase become immobile when the steam saturation is 0.05 \( (S_{VR}=0.05) \).

In spite of these limitations, the use of MULKOM and AUTOUGH2 for modelling geyser processes is attractive because, as mentioned before, it may provide some insight into the behaviour of the system as a whole and give estimates for the mass and the heat flows to the atmosphere which cannot be obtained from the simple mathematical models. Also it is able to model the complete transient behaviour of geyser activity and gives a complete description of two-phase flow. In the present study the validity of the models are checked by comparing the model solutions either with the solutions from mathematical models or with experimental data.

A simple conceptual model of a geyser given by Steinberg et al. (1981a), used earlier by the author in Chapters 4 and 5, is also used as the basis for models set up in the present work using MULKOM and AUTOUGH2 simulators (see Fig. 6.1. for the conceptual model and the parameters). Details are given here of the numerical model used, the simulation process and the results obtained.

![Conceptual model for Steinberg's problem](image)

(a) cold water bearing horizon; (b) low permeability rock; (c) hot water bearing horizon; (d) inflow of cold water; (e) inflow of hot water.

**Figure 6.1 Conceptual model for Steinberg's problem.**

6.2.1. Model description

For the numerical model the plumbing system is idealised as a vertical column as shown in Fig. 6.2. One block at the top (ATM 1) represents the atmosphere. The ten blocks below it (CHA 1 to CHA10) represent the channel. Each block is one meter thick making a total depth of ten meters. One large block at the bottom (CHA11) represents the geyser chamber. The cold water zone is represented by two recharge blocks, REC11 and COL11.
The pressure and the temperature in the cold water zone (REC11 and COL11) are 2.1 bar and 75°C respectively. To maintain constant pressure and temperature in the cold water zone, large volumes are assigned for these two blocks. A large volume is also assigned for block ATM 1 to maintain constant pressure and temperature at the atmosphere block. The constant upflow of hot water into the system is included in the model by an injection of hot water of 200°C at a constant rate of 1 kg/s.

The following assumptions are made in the model:

1. The geyser system is assumed to be a large cavity. The porosity of the chamber (block CHA11) and of the channel (blocks CHA 1 to CHA10) are thus assumed to be equal to one. The porosity of the cold water zone (blocks REC11 and COL11) is assumed to be equal to 0.3. Other rock properties such as density, heat conductivity and heat capacity are listed in Table 6.1.

*Figure 6.2 Computer model for Steinberg’s problem.*
2. The initial state is an approximation of the conditions which exist immediately after a geyser eruption stops. It is the same as that used by Steinberg et al. (1981a). The initial conditions are:

(a) The volume of the residual water after an eruption is 1.4 m$^3$. As the volume of the chamber is 2 m$^3$, this residual water thus occupies 70% of the volume of the chamber. It is assumed in the model that steam occupies 30% of the chamber volume. With this assumption, the steam saturation in block CHA11 (the chamber) is assumed to be 30%.

(b) The channel blocks (blocks CHA 1 to CHA10) are assumed to be filled by steam. The steam saturations in these blocks are thus assumed to be equal to one.

(c) The pressures and the temperatures in blocks CHA 1 to CHA11 are assumed to be 1.01325 bar and 100°C respectively.

(d) The pressure and the temperature in block ATM 1 are assumed to be at 1.01325 bar and 20°C respectively.

<table>
<thead>
<tr>
<th>Table 6.1 Rock Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber &amp; Channel</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>rock density</td>
</tr>
<tr>
<td>rock heat conductivity</td>
</tr>
<tr>
<td>rock specific heat</td>
</tr>
</tbody>
</table>

The model developed by Ingebritsen and Rojstaczer (1993) is similar to the present model in that it was developed with an idea that an eruption is caused by the boiling of water. Also they employ mass and heat balance equations and use Darcy's law to describe the flow processes. Their model is different from the present model in the following ways:

(a) Their model consists of a single standpipe or a shaft without a chamber, extending to a depth of 200 m with an area of 0.6 m x 1.5 m, surrounded by a low permeability rock that supplies water to the geyser.

(b) Porosity of the fracture zone is assumed to be 0.75.

(c) In their model there is no mass flux from the bottom. The heat input is represented by a constant heat flux from the bottom of 2.5 MW.

(d) The upper boundary is set to a constant pressure and enthalpy. At the side the pressure and the enthalpy are maintained at the hydrostatic boiling point. The upper and the lateral boundaries are the source of mass recharge.

(e) In the initial state the system is filled with saturated liquid with temperatures set equal to the boiling point temperatures corresponding to the hydrostatic pressure at a given depth.

(f) Their model considers only fully saturated flow.
6.2.2. MULKOM model

The geothermal simulator MULKOM was used in the early stage of this study to develop a fully transient activity of a geyser. As this simulator has no option for handling isothermal flow involving water, steam and air, a version of MULKOM which can handle a mixture of water, steam and CO₂ was used instead. At a later time the AUTOUGH2 simulator, which has an option for investigating flow of water, steam and air, became available and since then the AUTOUGH2 simulator has been used in this study. An unsaturated flow simulator is required because the plumbing of the geysers is usually located near the surface (1-70 m), within the unsaturated zone (a zone extending from the water table to the ground surface) where water and air co-exist at atmospheric pressure.

Modelling process

The numerical experiments were carried out to determine suitable values for the permeabilities of the channel, the chamber and the cold water zone. In the first few runs the permeability of the channel and the chamber were varied within the range 100 - 200 mD (1 x 10⁻¹³ m² to 2 x 10⁻¹³ m²). These are the permeability values commonly used in simulating geothermal reservoirs (O'Sullivan and McKibbin, 1988). A large number of numerical experiments were carried out by varying the permeabilities of the recharge zone, the channel and the chamber in an attempt to obtain a model that produced oscillatory behaviour. However, none of them exhibited oscillatory behaviour for a long period of time. Usually the model generated only two or three oscillatory cycles and thereafter it reached a steady state. The volumes of the recharge blocks were also varied in various attempts to produce oscillatory behaviour. In fact almost all parameters were varied in the many attempts made to produce oscillatory behaviour. Although different values of permeability can be assigned in each block, in the present study uniform permeability has been used for both the channel and the chamber.

The experiments described above were carried out using the Corey relative permeability curves with residual liquid saturation (S_{LR}) equal to 0.3 and residual vapour saturation (S_{VR}) equal to 0.05 (see Fig. 6.3). Experiments using the straight-line permeability functions produced similar results. The relative permeability curves are important in determining the nature of two-phase flow and the functions for large fractures are probably different from those for a porous medium. Therefore the relative permeabilities were treated as adjustable parameters. In particular the values of the residual water (S_{LR}) and steam saturations (S_{VR}) were varied. The models produced longer oscillatory behaviour when S_{LR} was decreased and S_{VR} increased. Long term oscillatory behaviour was obtained with S_{LR}=0 and S_{VR}=0.3 (see Fig. 6.3). Nevertheless, when the simulations were carried out for a very long time the model again reached a steady state. In attempts to produce at least one hundred oscillations the permeability
values and the volume of the recharge blocks were again varied while keeping $S_{LR}=0$ and $S_{VR}=0.3$. Even though the model is simple (only 13 blocks), the calculation process is very time consuming because of the small time steps required during phase changes. Therefore a large number of time steps (indeed a large amount of computer time) were required to allow a model to complete one hundred oscillations. Because the maximum number of time steps allowed in MULKOM is only 9999, several runs were necessary to obtain one hundred eruption cycles. Finally a model was obtained which was able to produce a simulation of the oscillatory transient processes of the activity of a geyser (using the parameters listed in Table 6.2). A total of 20,000 time steps was required to produce 100 eruptions. Experiments revealed that unless the maximum time increment was small (in this case 10 s) the actual time when the eruption occurred would be missed and the process would not be modelled adequately.

**Table 6.2**

<table>
<thead>
<tr>
<th>Model parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum time increment</td>
</tr>
<tr>
<td>Permeability in blocks in the chamber and the channel</td>
</tr>
<tr>
<td>Permeability in block REC11</td>
</tr>
<tr>
<td>Permeability in block COL11</td>
</tr>
<tr>
<td>Corey relative permeability function</td>
</tr>
<tr>
<td>residual water saturation ($S_{LR}$)</td>
</tr>
<tr>
<td>residual steam saturation ($S_{VR}$)</td>
</tr>
<tr>
<td>Volume of block REC11</td>
</tr>
<tr>
<td>Volume of block COL11</td>
</tr>
</tbody>
</table>

In this model the permeability in the chamber and in the channel is about $10^5$ greater than the matrix permeability value commonly used in simulating the behaviour of geothermal reservoirs. The permeability of the cold water zone (block REC11) is $10^2$ smaller than that in the chamber but it is still greater than the typical values for geothermal reservoirs. This permeable rock supplies 11 kg/s of cold water to the chamber after each eruption. Moreover, according to the model, the oscillatory behaviour of the geyser could be maintained only if there is a more permeable cold water zone further away to feed the geyser continuously.

The relative permeabilities of steam and water that produced the correct oscillatory nature for the activity of a geyser are those of Corey with values for $S_{LR}=0.0$ and $S_{VR}=0.3$. These are similar to the relative permeability curves derived by Gudmundsson et al. (1986) for flow in geothermal fractures but in their correlations both $S_{LR}=0.0$ and $S_{VR}=0.0$. The value of $S_{VR}=0.3$ can be related to the value of the vapour saturation in the chamber at the initial state. The residual water after the eruption, as previously mentioned, occupied 70% of the chamber. At the initial state, the liquid and the vapour saturation in the chamber are thus 0.7 and 0.3 respectively. The value of $S_{LR}=0.0$ means the liquid phase will become immobile only if the
liquid saturation is zero. In a vertical pipe flow, provided that the pressure gradient is adequate, both liquid and vapour are mobile ($S_{LR}= 0.0$ and $S_{VR}= 0.0$).

![Diagram showing relative permeability vs liquid saturation]

Figure 6.3 Relative permeability of water and steam as a function of liquid saturation.

**Geyser performance.**

As mentioned before, a simulation run with a total of 20,000 time steps produced 100 oscillatory cycles. The interval between eruptions varied from 15 to 16 minutes. Figs. 6.4a and 6.4b show the mass flow rate and the heat discharge to the atmosphere versus time respectively for the periods from 75600 s (21 hours) to 84600 s (23.5 hours). The most important and interesting results obtained from this study were that the model was able to simulate the eruption process itself and produce most aspects of behaviour that are observed in the real geysers, such as a steam discharge phase following the cessation of the eruption, water overflowing from the channel accompanied by intermittent discharge behaviour or several pulsating eruptions before the full column eruption occurs. Details of the mass and heat flow rate to the atmosphere in one cycle can be seen in Figs. 6.5a and 6.5b respectively. A cycle consists of four stages. These are:

1. **Quiet stage (B-C).**
   Over this period no liquid is discharged to the atmosphere.

2. **Pre-play stage (C-D).**
   This stage begins immediately after the water level reaches the mouth of the vent (C) and ends when the eruption begins (D). During this stage water overflows from the channel at about 2 kg/s accompanied by intermittent discharge behaviour.
(3) Full column eruption stage.
The beginning of the full column eruption is indicated in the model by a rapid increase in the mass flow rate of fluid discharged to the atmosphere (D). The model produced a maximum eruption rate of about 16 kg/s.

(4) Falling stage.
After the full column eruption ends (E) the mass flow rate gradually declines to zero (A).

The data for the duration of quiet, the duration of pre-play, the interval between eruptions, the duration of full column eruption, the maximum mass and heat discharge for the geyser are summarised in Table 6.3. Even with a very large recharge block the pressure in the cold water zone decreases slowly with time. After the geyser erupts 100 times the pressure in REC11 drops from 2.1 bar to 2.0924 bar which in turn causes the inflow rate of cold water to decrease with time and results in a decrease in the interval between eruptions from 960 s to 900 s. It seems that larger recharge blocks than those listed in Table 6.2 may be necessary to maintain oscillatory behaviour with a constant interval between eruptions.

<table>
<thead>
<tr>
<th>Duration of quiet (s)</th>
<th>Duration of overflowing or pre-play (s)</th>
<th>Interval between eruptions (minutes)</th>
<th>Duration of full column eruption (s)</th>
<th>Maximum mass flow rate discharged (kg/s)</th>
<th>Maximum heat discharged (MW)</th>
<th>Type of surface features</th>
</tr>
</thead>
<tbody>
<tr>
<td>240-260</td>
<td>640-710</td>
<td>15-16</td>
<td>110-120</td>
<td>15.9-16.3</td>
<td>8.1-8.3</td>
<td>geyser p.b.s</td>
</tr>
</tbody>
</table>

*geyser p.b.s=geyser with pulsating spring behaviour*
Figure 6.4a Mass flow rate discharge to the atmosphere (Steinberg-like MULKOM model)

Figure 6.4b Heat flow rate discharged to the atmosphere (Steinberg-like MULKOM model)
Figure 6.5a Mass flow rate discharge to the atmosphere (Steinberg-like MULKOM model)
B-C=quiet stage
C-D=overflowing (pre-play) stage
D-A=full column eruption stage
A-B=falling stage

Figure 6.5b Heat discharge to the atmosphere (Steinberg-like MULKOM model)
B-C=quiet stage
C-D=overflowing (pre-play) stage
D-A=full column eruption stage
A-B=falling stage
Figure 6.5c  The inflow rate of cold water to the chamber (Steinberg-like MULKOM model)
A-B= Chamber filling stage  C-D=heating of the water in the chamber to boiling
B-C=Channel filling stage  D-A=vigorous boiling

Figure 6.5d  The steam saturation in the chamber (Steinberg-like MULKOM model)
A-B= Chamber filling stage  C-D=heating of the water in the chamber to boiling
B-C=Channel filling stage  D-A=vigorous boiling
Figure 6.5e The pressure in the chamber (Steinberg-like MULKOM model)
A-B = Chamber filling stage  
B-C = Channel filling stage  
C-D = Heating of the water in the chamber to boiling  
D-A = Vigorous boiling

Figure 6.5f The temperature in the chamber (Steinberg-like MULKOM model)
A-B = Chamber filling stage  
B-C = Channel filling stage  
C-D = Heating of the water in the chamber to boiling  
D-A = Vigorous boiling
Processes inside the system.

Figs. 6.5c and 6.5f illustrate the inflow rate of water to the chamber, the steam saturation, the pressure and the temperature in the chamber respectively. According to the model, the processes within the system consist of four stages:

Stage-1 : Filling of the chamber (A-B)
Stage-2 : Filling of the channel (B-C)
Stage-3 : Heating of the water in the chamber to boiling (C-D)
Stage-4 : Vigorous boiling (D-A)

In the model the filling of the chamber and the channel takes place during the falling and the quiet stage. The heating of water in the chamber takes place during the overflowing stage and vigorous boiling occurs during the eruption. The processes inside the system are described in more detail in the following sections.

The filling of the chamber is indicated by a rapid increase in the inflow rate of cold water to the system and a decrease in the steam saturation in block CHA11 (see A-B in Figs. 6.5c and 6.5d respectively). The filling of the chamber is completed when the steam saturation in block CHA11 is equal to zero (B).

Fig. 6.6 shows the water saturation, the pressure and the temperature profile inside the system at the end of the chamber filling. Down to 8 m depth the pressure and temperature are equal to 1.01325 bar and 100°C respectively. The water saturation profile indicates that this part of the channel is filled by two-phase fluid, in which steam is dominant (water saturation is less than 0.25). Below it, the water saturations are higher than 0.8 indicating that water is dominant. In this part of the system the pressures and the temperatures are higher than 1.01325 bar and 100°C respectively. The water level at the end of the chamber filling is approximately at the 8 m depth level.

The filling of the channel begins immediately after the chamber has filled. The processes within the system during channel filling are illustrated here in Fig. 6.7. The figure shows the water saturation, the pressure, and the temperature-with-depth profiles at four selected times. Profile 1 shows the conditions at the beginning of the channel filling. Profiles 2 and 3 show the conditions within the system when the water levels are at about 5 m depth and 3 m depth respectively. Profile 4 shows the conditions when the channel has filled with water.
After the channel has filled the pressure in the system remain almost constant, but the temperature increases with time (see Fig. 6.8). As the temperature increases flashing occurs in the upper part of the channel where the temperature is higher than the boiling temperature, resulting in an intermittent discharge behaviour at the surface. This is indicated by the increase in the steam saturation (decrease in water saturation) at the upper part of the channel. After
several minutes, when the water temperature in the chamber reaches 120.5°C, the water in the chamber begins to boil (profile 9). The model suggests that this is the time when the eruption begins. Thereafter boiling in the chamber becomes more vigorous (the steam saturation increases) whilst the pressure and the temperature within the system build up rapidly to 2.2 bar and 123.4°C respectively (see Fig. 6.9). The model suggests that by this time the mass flow rate discharging to the atmosphere reaches a maximum value. Thereafter, the pressure and the temperature drop rapidly, and the processes described above are repeated.

Figure 6.8 Conditions during the overflowing stage (Steinberg-like MULKOM model).

Figure 6.9 Conditions during the eruption (Steinberg-like MULKOM model).
Comparison between analytical and numerical solutions.

To compare the model solution with the analytical solution, calculations were carried out using the Steinberg model (Chapter 4) and the variable density model (Chapter 5). Fig. 6.10 compares the solution obtained from the MULKOM and that from the Steinberg models. In general they have similar characteristic. These two models differ in three ways. Firstly, in the MULKOM model, the inflow rate of cold water during the filling of the chamber is never constant. Secondly, in the MULKOM model, after the water in the chamber reaches the boiling point temperature the pressure in the chamber increases very rapidly to a higher value than that in the cold water zone, resulting in an outflow to the cold recharge zone (D-A in Fig. 6a). Thus in the numerical model during the eruption some water flows out from the chamber. The mathematical model, however, did not include this process. Thirdly, in the MULKOM model, the pressure and the temperature in the chamber after an eruption never drop to atmospheric pressure and the corresponding boiling point temperature (1.01325 bar and 100°C).

The agreement between the MULKOM model and the variable density model using the Duns and Ros correlation is very much the same as that described above (Appendix F). The variable density model using the Duns and Ros correlation predicts that slug flow is formed at the bottom of the channel only 20 s after water in the chamber reaches its boiling point temperature. The match with the solution from the variable density model using the Orkiszewski correlation is rather poor (see Appendix F) because, after water in the chamber reaches its boiling point, a longer time is required for the slug flow to be formed at the bottom of the channel.

Comparison with the model of Ingebritsen and Rojstaczer (1993).

The model developed by Ingebritsen and Rojstaczer (1993), previously described in section 6.2.1, produces oscillatory behaviour over two to three eruption cycles. The interval between eruptions is about 21 minutes and the eruption rates are about 50 kg/s. The authors, however, do not report on whether this cyclic behaviour continues after three cycles. Also they did not compare the solution with previous analytical solutions such as those produced by Steinberg. The permeability of the fracture is the same order of magnitude as that used in the present model, i.e $10^{-8}$ m². The side rock has a permeability $10^3$ to $10^4$ times smaller than that of the fractures. Their model uses a straight-line permeability function with $S_{LR}=0.3$ and $S_{VR}=0.0$. Their model shows that the drive for an eruption is the conversion of water to steam. Steam drives the water, mainly from depths of <40 m (total depth is 200 m), up through the vent.
No sensitivity study was undertaken by the author using the MULKOM model. The results of a sensitivity study using AUTOUGH2 model will be described later in this chapter. The sensitivity of the model developed by Ingebritsen and Rojstaczer (1993) can be summarised as follows:

(i) Changes in the permeability and porosity of the geyser pipe have a significant effect on the interval between eruptions. An increase in the permeability of the geyser pipe will cause the geyser to erupt more frequently. In contrast, an increase in the porosity will cause the interval between eruptions to increase.

(ii) Changes in the heat input had little effect on the interval between eruptions but they significantly affect the eruption rate.

(iii) Changes in the inflow temperature seem to have no significant effect on the interval between eruptions but they affect the eruption rate.

(iv) The interval between eruptions and the eruption rate is dependent on the length of the channel. A longer channel produces a longer interval between eruptions and a larger eruption rate.

(v) Changes in the cross sectional area of the channel have a significant effect on the interval between eruptions only if the size of the channel is fairly small.

(vi) Changes in the atmospheric pressure induce changes in lateral recharge. An increase in the atmospheric pressure causes a decrease in the lateral recharge which leads to an increase in the frequency of eruption.

(vii) Strains induced by earth tides could also induce changes in lateral recharge and modify the behaviour of geysers.

(viii) Ground motion (seismicity) may cause the permeabilities of the fracture and of the side rocks to increase and the frequency of eruption to increase.
Figure 6.10 The inflow of cold water, the pressure and the temperature of water in the chamber

- MULKOM model
- Steinberg model

A-B = Filling of the chamber
B-C = Filling of the channel
C-D = Heating to boiling
D-A = Vigorous boiling

A'-B' = Filling of the chamber
B'-C' = Filling of the channel
C'-D' = Heating to boiling (eruption)
6.2.3. AUTOUGH2 model.

The same problem (see section 6.2.1) was simulated using the AUTOUGH2 simulator. All model parameters were the same as those used in the MULKOM model (Tables 6.1 and 6.2). Without tuning any parameters the model produced oscillatory behaviour with characteristics similar to the MULKOM model (see Figs. 6.11a, 6.11b and Appendix F for other plots). According to the model the activity of a geyser in a cycle also consists of four stages, namely: (1) quiet stage, (2) pre-play stage, (3) full column eruption stage and (4) falling stage. As in the MULKOM model, the inflow rate of cold water during the filling of the chamber is never constant and the pressure and the temperature in the chamber after an eruption never drop to atmospheric pressure and the corresponding boiling point temperature (1.01325 bar and 100°C). Nevertheless, there are some differences between the MULKOM and the AUTOUGH2 model, which is probably because the MULKOM-CO2 simulator does not accurately simulate the unsaturated zone above the water table. These are:

(a) In the AUTOUGH2 model the cavern pressure is slightly lower resulting in a higher cold inflow, a longer interval between eruptions (by 2-3 minutes) and a higher eruption rate (by 2 kg/s).

(b) In the MULKOM model, the intermittent discharge behaviour during the pre-play stage is also more erratic than that in the AUTOUGH2 model (see Figs. 6.3 and 6.11a for comparison).

![Mass flow rate of fluid discharged to the atmosphere (AUTOUGH2 model)](image-url)
6.3. Modelling laboratory experiments using AUTOUGH2

In the second part of this modelling study the AUTOUGH2 simulator was used to simulate the behaviour of the physical model, previously discussed in Chapters 3. The conceptual model used has been presented previously in Fig. 4.5 (Chapter 4). Here the chamber has only one feed point for the inflow of cold water but it has a constant heat input at the bottom of the chamber. The dimension of the geyser is the same as that listed in Table 4.6 (Chapter 4). As data are available from the experimental study the model was calibrated by matching the inflow rate of water to the chamber and the temperatures in the chamber and in the bottom, the centre and the top end of the channel.

6.3.1. Model description

Fig. 6.12 shows the grid layout for the model. Block LAB 1, 0.1 m thick, represents the cone. The ten blocks below it, blocks LAB 2 to LAB11, each 0.16 m thick, represent the channel. The cross section area of the cone and the channel are equal, 0.00116 m². Block LAB 12 represents the geyser chamber. The atmosphere is represented in the model by block ATM 1. To maintain constant pressure and temperature in the atmospheric block a large volume is assigned to the ATM block. The constant heat input is included in the model by an injection of heat at a constant rate of 2 kW or 2 kJ/s. The water source is represented in the model by block REC12.
The rock properties are set to be the same as those used in the previous study (Table 6.1). Two experiments were simulated. In the first experiment the chamber was fed by cold water of 13°C. In the second experiment the chamber was fed by water of 40°C. The model parameters used are given Table 6.4. The steam saturation at the initial state is determined from the volume of the residual water after the eruption.

6.3.2. Numerical Experiments

The same modelling process as that described in section 6.2.2 was followed for this study. To begin with, the permeability values, the relative permeability curve and the maximum time increment were set equal to those listed in Table 6.2. Some tuning of these parameter values was necessary to obtain a good match to the observed data. The model parameters were varied until the calculated results matched the observed data. The best models for the two cases were obtained using the model parameters listed in Table 6.5.
### Table 6.4
Model parameters

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial steam saturation (fraction)</td>
<td>0.262</td>
<td>0.185</td>
</tr>
<tr>
<td>Atmospheric pressure (bar)</td>
<td>1.008</td>
<td>1.014</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>15.5</td>
<td>17.4</td>
</tr>
<tr>
<td>Pressure in block REC12 (bar)</td>
<td>1.4</td>
<td>1.265</td>
</tr>
<tr>
<td>Temperature in block REC12 (°C)</td>
<td>13.0</td>
<td>40.0</td>
</tr>
</tbody>
</table>

### Table 6.5
Model parameters.

|                                | Case 1       | Case 2       |
|                                | 10 s         | 10 s         |
| Maximum time increment         |              |              |
| Permeability of the atmosphere block (ATM) | 1.00E-07 m²  | 1.0E-07 m²  |
| Permeability of the channel and the chamber (LAB 1 to LAB11) | 0.80E-08 m²  | 0.8E-08 m²  |
| Permeability of the cold water zone (REC12) | 0.45E-09 m²  | 1.2E-08 m²  |
| Corey relative permeability function |              |              |
| residual water saturation (S_{LR})   | 0.0         | 0.0         |
| residual steam saturation (S_{VR})   | 0.0         | 0.0         |
| Volume of block REC12            | 0.2E+10 m³  | 0.2E+10 m³  |

#### 6.3.3. Modelling Results

Figs. 6.13 and 6.14 compare the model results with the observed data for experiments 1 and 2 respectively. The agreement between the calculated and the actual rates of cold inflow is not good, but the total mass flowing to the chamber is nearly the same in the numerical model as in the experiment. This results in a good agreement in the interval between eruptions. The temperatures in the chamber predicted by the model are lower than the actual values, but those at the bottom of the channel match very well. The model, however, was not able to match the temperatures at the centre of the channel and at the top end of the channel. The predicted temperatures are greater than the actual values. This is because in the laboratory model the channel was not insulated, so there are some heat losses to the surrounding. The computer model, on the other hand, did not include the surroundings.

In the laboratory model, water in the chamber should boil vigorously for an eruption to occur. It is the rising of the large bubbles and slugs of liquids that cause the ejection of water to the atmosphere. In the computer model an eruption (a rapid increase in the mass discharge to the atmosphere) occurs as soon as the steam saturation is greater than zero indicating that the water in the chamber reaches its boiling point.
Figure 6.13 Results of the simulation for case 1. (a) Inflow rate of water to the chamber, (b) Pressure in the chamber, (c) Temperature in the chamber, (d) Temperature in the bottom of the channel, (e) Temperature in the centre of the channel, (f) Temperature in the top end of the channel, (g) Mass flow rate to the atmosphere, (h) Heat flow rate to the atmosphere.
Figure 6.14 Results of the simulation for case 2. (a) Inflow rate of water to the chamber, (b) Temperature in the chamber, (c) Temperature in the bottom of the channel.
6.4. Sensitivity Study

This section discusses the sensitivity of a geyser to:

(i) changes in the permeability
(ii) changes in the rate and temperature of the hot inflow
(iii) changes in the pressure and temperature of the cold water zone
(iv) changes in the atmospheric pressure and the ambient temperature
(v) changes in the size of the vent

Quantitative answers on how the activity of a geyser is affected by changes in these parameters can be obtained from the numerical models by comparing plots of mass flow rate discharge to the atmosphere versus time for various cases. The effect of changes in these parameters on the interval between eruptions and eruption rate, as well as the duration of the falling stage, the duration of quiet stage, the duration of the pre-play stage and the duration of eruption, are discussed. Also discussed in this chapter are some results of simulation using Corey relative permeability curves with $S_{LR}=0.3$ and $S_{VR}=0.05$. The Steinberg-like AUTOUGH2 model discussed in section 6.2.3 was used as the base case (see Tables 6.1 and 6.2 for the model parameters).

6.4.1. Permeability of the channel and the chamber

Four cases were simulated to investigate the sensitivity of the geyser to permeability of the chamber and the channel. As in the base case, a uniform permeability was used for both the chamber and the channel which for the four cases studied here are $2 \times 10^{-8}$ m$^2$, $5 \times 10^{-8}$ m$^2$, $7 \times 10^{-8}$ m$^2$ and $9 \times 10^{-8}$ m$^2$ (in the base case the permeability of the channel and the chamber is $8 \times 10^{-8}$ m$^2$). Fig. 6.15 shows the mass flow rate discharge to the atmosphere versus time for $k = 2 \times 10^{-8}$ m$^2$ and $k = 9 \times 10^{-8}$ m$^2$. Fig. 6.16 compares the temperature, the pressure and the inflow rate versus time respectively for the two cases. The results of simulations for other cases are not presented here but they are summarised in Figs. 6.17 which shows the maximum eruption rate, the maximum heat flow rate, the duration of eruption, the duration of the falling stage, the duration of the quiet stage, the duration of the cavern filling, the duration of the pre-play stage and the interval between eruptions for permeabilites ranging from $2 \times 10^{-8}$ m$^2$ to $9 \times 10^{-8}$ m$^2$.

The results of simulation show that a cavern with smaller permeability erupts more frequently and produces a smaller eruption rate but a longer duration of eruption (Fig. 6.17). In the case of $k = 9 \times 10^{-8}$ m$^2$, for example, the interval between eruptions is 1010 s, the maximum eruption rate is 18.6 kg/s and the duration of eruption is 120 s whereas in the case of $k = 2 \times 10^{-8}$ m$^2$ the interval between eruptions is 950 s, the maximum eruption rate is only 7.8 kg/s but the duration of eruption is almost doubled (220 s).
The processes inside the system are similar to those discussed earlier except that pressure, particularly after the water level reaches the surface, is higher in the cavern with a smaller permeability (Fig. 6.16a). A higher cavern pressure after the water level reaches the surface has the effect of lowering the inflow rate of cold water to the chamber during the pre-play stage (Fig. 6.16b). This in turn causes a more rapid increase in temperature (Fig. 6.16c) and hence less time is required to bring water in the chamber to boiling. The duration of the pre-play stage thus decreases with decreasing permeability (Fig. 6.17f).

A smaller permeability also has the effect of increasing the outflow from the chamber to the cold water zone during the eruption stage (as can be seen in Fig. 6.16c, the inflow rate of cold water has larger negative values). Therefore the volume of the residual water is smaller (the steam saturation in the chamber is greater) and so the pressure in the chamber after an eruption is lower than that in the chamber with a larger permeability. Because the volume of the residual water is less, it takes longer to refill the cavern with a smaller permeability (see Fig. 6.17f), although the maximum inflow rate of cold water is higher (see Fig. 6.17e). Hence, both the duration of the falling stage and the duration of the quiet stage increases as the permeability decreases.

Another noteworthy difference is in the behaviour of the surface discharges during the pre-play stage. In all cases water periodically rises and falls during the pre-play stage but in the case of $k = 2 \times 10^{-8}$ m$^2$ the surface discharge hardly ever drops to zero (Fig. 6.15b).

Fig. 6.18 compares the duration of the cavern filling, the duration of the pre-play stage and the interval between eruptions obtained from the AUTOUGH2 model to those obtained from the Steinberg model and the Variable Density model, as calculated using parameters listed in Tables 4.2 and 6.6. As can be seen, those calculated using the Variable Density Model and the Duns and Ros correlation are the closest to those obtained from the AUTOUGH2 model.

<table>
<thead>
<tr>
<th>Permeability of the channel and the chamber (m$^2$)</th>
<th>Inflow rate of cold water (kg/s) During the chamber filling ($G_{c1}$)</th>
<th>After the channel is filled with water ($G_{c2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 x 10$^{-8}$</td>
<td>12.0</td>
<td>1.24</td>
</tr>
<tr>
<td>8 x 10$^{-8}$</td>
<td>12.2</td>
<td>1.20</td>
</tr>
<tr>
<td>7 x 10$^{-8}$</td>
<td>12.3</td>
<td>1.19</td>
</tr>
<tr>
<td>5 x 10$^{-8}$</td>
<td>12.7</td>
<td>1.11</td>
</tr>
<tr>
<td>2 x 10$^{-8}$</td>
<td>13.3</td>
<td>0.90</td>
</tr>
</tbody>
</table>
(a) Permeability of the channel and the chamber is \( 9 \times 10^{-8} \text{ m}^2 \)
(interval between eruptions = 1010 s, durations of eruptions = 120 s).

(b) Permeability of the channel and the chamber is \( 2 \times 10^{-8} \text{ m}^2 \).
(interval between eruptions = 950 s, duration of eruptions = 220 s)

Figure 6.15 Mass flow rate discharge to the atmosphere versus time for \( k = 9 \times 10^{-8} \text{ m}^2 \) and \( k = 9 \times 10^{-8} \text{ m}^2 \)
(AUTOUGH2 model).
Figure 6.16 The pressure in the chamber (a), the inflow rate of cold water to the chamber (b) and the temperature in the chamber (c) versus time for $k = 9 \times 10^{-8} \text{ m}^2$ and $k = 2 \times 10^{-8} \text{ m}^2$ (AUTOUGH2 model).
Figure 6.17 Sensitivity of geyser performance to changes in permeability of the channel and the chamber (AUTOUGH2 model).
Figure 6.18 Sensitivity of geyser performance to changes in permeability of the channel and the chamber.
6.4.2. Permeability of the cold recharge zone

Three cases are compared in order to investigate how the activity of a geyser may be affected by changes in the permeability of the cold recharge block (REC11). Fig. 6.19 shows the mass flow rate discharge to the atmosphere versus time predicted by the model for \( k = 3.0 \times 10^{-11} \) m\(^2\) and \( k = 2.2 \times 10^{-11} \) m\(^2\) (in the base case \( k = 2.5 \times 10^{-11} \) m\(^2\)). The maximum eruption rate, the maximum heat flow rate, the inflow rate of cold water, the duration of the eruption, the duration of the falling stage, the duration of the quiet stage and the interval between eruptions for the three cases are compared in Fig 6.20. As expected, a decrease in the permeability causes the inflow rate of cold water to the chamber to decrease resulting in a longer duration of the cavern filling (a longer duration of the quiet stage) and a shorter duration of the pre-play stage. Both the interval between eruptions and the duration of eruption decreases as the permeability decreases but the maximum eruption rates are very much the same. A decrease in permeability by 12% from \( 2.5 \times 10^{-11} \) m\(^2\) to \( 2.2 \times 10^{-11} \) m\(^2\), for example, causes the maximum inflow rate of cold water to decrease from 12.2 kg/s to 10.5 kg/s and the inflow rate of cold water during the pre-play stage to decrease from 1.2 kg/s to 1.13 kg/s. This in turn causes the duration of the falling stage and the duration of the quiet to increase, although only by 10 s and 20 s respectively, but the duration of the pre-play stage decreases by 18% from 770 s to 630 s. With these changes the interval between eruptions decreases by 11% (from 1000 s to 890 s) and the duration of eruption decreases by 8% (from 120 s to 110 s) but the maximum eruption rate remains essentially constant at 17.5 kg/s.

Fig. 6.21 compares the duration of the cavern filling, the duration of the pre-play stage for the three cases from the AUTOUGH2 model with those obtained from the Steinberg model and the variable density model. As before, the variable density model using the Duns and Ros correlation give similar results to those obtained from the AUTOUGH2 model.

6.4.3 Inflow rate of hot water

Mathematical modelling studies, previously discussed in Chapters 4 and 5, showed that an increase in the inflow rate of hot water (\( \text{G} \)) causes both the duration of the cavern filling and the duration of the pre-play stage to decrease which in turn causes the interval between eruptions to decrease. The effect of changes in \( \text{G} \) predicted by the numerical model can be seen in Fig. 6.22 which shows the mass flow rate discharge to the atmosphere versus time for three different values of \( \text{G} \), i.e. \( \text{G} = 1 \) kg/s (base case), \( \text{G} = 2 \) kg/s and \( \text{G} = 0.8 \) kg/s. Fig. 6.23 shows the effect of these changes on the heat flow rate, the duration of eruption, the duration of the falling stage, the duration of the quiet stage, the inflow rate of cold water, the duration of cavern filling and the interval between eruptions.
(a) Permeability of the channel and the chamber is $3.0 \times 10^{-11} \text{ m}^2$
(interval between eruptions = 1220 s, duration of eruptions = 130 s).

![Graph showing mass flow rate of fluid discharge to the atmosphere.]

(b) Permeability of the channel and the chamber is $2.2 \times 10^{-11} \text{ m}^2$.
(interval between eruptions = 890 s, duration of eruptions = 110 s)

![Graph showing mass flow rate of fluid discharge to the atmosphere.]

*Figure 6.19 Mass flow rate discharge to the atmosphere versus time for permeability of the recharge block of 3.0 $\times 10^{-11}$ m$^2$ and 2.2 $\times 10^{-11}$ m$^2$ (AUTOUGH2 model).*
Figure 6.20 Sensitivity of geyser performance to changes in the permeability of the recharge block (AUTOUGH2 model).
Figure 6.21 Sensitivity of geyser performance to changes in the permeability of the recharge block.
The model shows that if $G_h$ increases, the surface discharge during the pre-play stage becomes larger in magnitude and more erratic at the early stage (see Figs. 6.22a and 6.22b). The eruption rate also increases but the duration of eruption is slightly shorter (see Fig. 6.23). The model also shows that the duration of the falling stage increases as $G_h$ increases, although only very slightly. If $G_h$ increases, the duration of the quiet stage becomes shorter because less time is required to re-fill the cavern after an eruption.

In the AUTOUGH2 model an increase in $G_h$ has the effect of increasing the cavern pressure resulting in a lower inflow of cold water to the chamber. As can be seen in Fig. 6.24, an increase in $G_h$ from 1 kg/s to 2 kg/s causes $G_{c1}$ to decrease from 12.2 to 10.4 kg/s and $G_{c2}$ to decrease from 1.2 kg/s to 1.13 kg/s. Changes in $G_h$, coupled with changes in cold inflow ($G_c$), certainly will have greater effect on the performance of a geyser than change in $G_h$ alone. With the changes in $G_h$ and $G_c$ as mentioned above, the duration of the falling stage increases only by 10 s and the duration of the quiet stage decreases by only 20 s but, as the cavern temperature rises faster, the duration of the pre-play stage decreases by 80% (from 770 s to 150s).

Fig. 6.25 compares the duration of the cavern filling, the duration of the pre-play stage and the interval between eruptions calculated by the AUTOUGH2 model to those calculated using the Steinberg model and the Variable Density model. As before, the variable density model using the Duns and Ros correlation give closest results to those obtained from the AUTOUGH2 model.

In nature changes in the rate of inflow of hot water feeding a geyser may be caused by several factors. They are:

(a) Changes in the flow pattern because of the existence of subsurface connection with other springs or geysers. Marler (1951) and Bryan (1986) believed that interchanging behaviour between many geysers and springs in the Yellowstone National Park, called by Marler (1951) an *exchange of function*, is because they are connected underground and so from time to time there is a shift in the direction of the flow resulting in a great irregularity in the activity of the geysers.

(b) A decline in the pressure of the geothermal reservoir due to extensive extraction of hot fluids from the geothermal reservoir. Examples are the geysers associated with Wairakei and Rotorua geothermal fields in New Zealand (Grant et al., 1982) and those at the Steamboat Springs, Nevada (Collar and Huntley, 1990).
(a) Inflow rate of hot water = 1 kg/s (interval between eruptions = 1000 s).

(b) Inflow rate of hot water = 2 kg/s (interval between eruptions = 370 s)

(c) Inflow rate of hot water = 0.8 kg/s (interval between eruptions = 1690 s)

Figure 6.22 Mass flow rate of fluid discharge to the atmosphere versus time for $G_h = 1$ kg/s, $G_h = 2$ kg/s and $G_h = 0.8$ kg/s (AUTOUGH2 model).
Figure 6.23 Sensitivity of geyser performance to changes in the rate of hot inflow.
Figure 6.24 Inflow rate of cold water versus time for $G_h = 1 \text{ kg/s}$, $G_h = 2 \text{ kg/s}$ and $G_h = 0.8 \text{ kg/s}$ (AUTOUGH2 model).

(a) $G_h = 1 \text{ kg/s}$ (interval between eruptions = 1000 s).

(b) $G_h = 2 \text{ kg/s}$ (interval between eruptions = 370 s).

(c) $G_h = 0.8 \text{ kg/s}$ (interval between eruptions = 1690 s).
Figure 6.25 Sensitivity of geyser performance to changes in the rate of hot inflow.
(c) Changes in the nature of the rock because of the earthquake activity. An earthquake may open or close up some fractures and alter the flow pattern. In some places many long-dormant geysers began eruption and the frequency of eruption of already active geysers increased after earthquake activity (Rinehart, 1972, 1980 and Bryan, 1986).

6.4.4. Temperature of hot and cold inflow

Changes in temperature of hot inflow.

The mathematical models have shown that a decrease in the temperature of the hot inflow ($T_h$) causes the duration of the pre-play stage to increase but the duration of the cavern filling is virtually unchanged as the mass flow rate of the water feeding the geyser is the same. Figs. 6.26a and 6.26b show results of a sensitivity study using the numerical model in which the temperature of the hot inflow ($T_h$) is varied by $20^\circ$C. The model shows that a decrease in $T_h$ can cause the eruption rate and the heat flow rate to decrease but the duration of the eruption to increase. There is also a slight increase in $G_c$. Hence, a decrease in $T_h$ not only causes the temperature in the cavern to rise at a slower rate and result in an increase in the duration of the pre-play stage but it also causes the duration of the cavern filling to decrease. With these changes, the interval between eruptions increases as $T_h$ decreases. The opposite effect will result if $T_h$ increases. A 10% increase in $T_h$ from 200$^\circ$C to 220$^\circ$C, for example, causes both the maximum eruption rate and the maximum heat flow rate to increase by 13%. The duration of eruption, however, decreases by 17% (20 s). The duration of the cavern filling increases only very slightly (10 s) but the duration of the pre-play stage decreases by 36% from 770 s to 490 s. With these changes the interval between eruptions decreases by 27% from 1000 s to 730 s.

The duration of the cavern filling, the duration of the pre-play stage and the interval between eruptions obtained from the numerical model are compared with those obtained from the Steinberg model and the Variable Density model in Fig. 6.26b. As can be seen, those obtained from the Steinberg model and the variable density model using the Duns and Ros correlation are the closest to those obtained from the AUTOUGH2 model.

In nature a decline in the temperature of hot water feeding a geyser may be caused by the extraction of heat from the geothermal reservoir. The temperature of the hot inflow may increase as a result of opening of fractures caused by earthquakes.
(i) Temperature of hot inflow = 200°C (interval between eruptions = 1000 s)

(ii) Temperature of hot inflow = 220°C (interval between eruptions = 730 s)

(iii) Temperature of hot inflow = 180°C (interval between eruptions = 1900 s)

Figure 6.26a Mass flow rate of fluid discharge to the atmosphere versus time for $T_h = 180^\circ$C, $T_h = 200^\circ$C and $T_h = 220^\circ$C (AUTOUGH2 model).
Figure 6.26b Sensitivity of geyser performance to changes in the temperature of hot inflow.
**Changes in temperature of cold inflow.**

The temperature of ground water (cold water) at most places it is fairly constant during the year, but in some places it varies with the seasons. The mathematical models have also shown that a decrease in the temperature of recharge water \( (T_c) \) causes the duration of the pre-play stage to increase but the duration of the cavern filling is virtually unchanged as the mass flow rate of the water feeding the geyser \( (T_c) \) is the same. A sensitivity study using the numerical model showed that raising \( T_c \) would also cause the activity of the geyser during the pre-play stage to be more erratic (see Fig. 6.27a). Decreasing the temperature would counteract this effect causing water to overflow quietly at the beginning of the pre-play stage.

In the numerical model, changes in \( T_c \) will affect not only the duration of the pre-play stage but also the duration of the cavern filling. As the duration of the eruption increases, the total mass discharge increases and the volume of the residual water after an eruption decreases with decreasing \( T_c \). The time required to fill up the cavern will thus increase as \( T_c \) decreases. As in the mathematical models, a decrease in \( T_c \) also causes the cavern temperature to rise at slower rate results in a longer duration of the pre-play stage and hence a longer interval between eruptions. Changes in \( T_c \) do not significantly change the eruption rate. The duration of eruption, however, increases as \( T_c \) decreases, although only very slightly.

The duration of the cavern filling, the duration of the pre-play stage for the three cases from the numerical model are compared with those obtained from the Steinberg model and the Variable Density model in Fig. 6.27b. Again, those obtained from the Variable Density Model using the Duns and Ros correlation are the closest to those obtained from the AUTOUGH2 model.

**6.4.5. Ambient temperature.**

The effect of changes in the ambient temperature on the performance of a geyser is illustrated in Fig. 6.28. The model shows that a decrease in the ambient temperature only slightly extends the duration of the pre-play stage and thus only slightly lengthens the interval between eruptions, and vice versa. If other parameters are unchanged, which is very unlikely to occur in nature, one might expect that a geyser will play more frequently during summer and less frequently during winter. There is evidence to suggest that there is a seasonal influence on geyser activity. For the Rustic geyser at the Yellowstone National Park (USA), for example, according to Bryan (1986) the interval between eruptions decreases as the summer season progresses.
(i) Temperature of cold inflow = 75°C (interval between eruptions = 1000 s).

![Graph showing mass flow rate of fluid discharge to the atmosphere over time for different temperature conditions.]

(ii) Temperature of cold inflow = 90°C (interval between eruptions = 760 s).

(iii) Temperature of cold inflow = 60°C (interval between eruptions = 1350 s)

Figure 6.27a Sensitivity of geyser performance to changes in the temperature of cold inflow.
Figure 6.27b Sensitivity of geyser performance to changes in the temperature of cold inflow.
(i) Ambient temperature = 20°C (interval between eruptions = 1000 s).

(ii) Ambient temperature = 15°C (interval between eruptions = 1010 s).

(iii) Ambient temperature = 10°C (interval between eruptions = 1020 s).

Figure 6.28 Sensitivity of geyser performance to changes in the ambient temperature.
6.4.5. Pressure of cold water zone

In nature the pressure of the cold water zone is variable depending on the water levels. When recharge to a ground water aquifer exceeds the discharge from it, the water level rises resulting in an increase in the pressure in the cold water zone, and vice versa. Recharge to the ground water aquifer varies from day to day and from season to season. Low rainfall for a period of time may cause a decline in the ground water levels, for example.

Fig. 6.29 illustrates the effect of changes in the pressure in the recharge zone on the performance of a geyser. A decrease in the pressure in the recharge zone (a decrease in the water level) will obviously decrease the inflow rate of cold water to the chamber and this in turn causes the duration of the cavern filling to increase and the duration of the pre-play stage to increase. For the model discussed here, a decrease in the pressure in the cold water zone from 2.1 bar to 2.05 bar also causes the geyser to lose its intermittent behaviour during the pre-play stage.

(i) Pressure at the cold water zone = 2.1 bar (interval between eruptions = 1000 s)

(ii) Pressure at the cold water zone = 2.05 bar (interval between eruptions = 730 s)

Figure 6.29 Sensitivity of geyser performance to changes in the pressure of the cold recharge zone.
6.4.7. Atmospheric pressure

It has been observed that changes in the atmospheric pressure may significantly affect the activity of a geyser (Rinehart, 1972) i.e. a decrease in atmospheric pressure lengthens the interval between eruptions and an increase in pressure shortens it. Two cases are compared in Fig. 6.30 to illustrate the effect of atmospheric pressure on the activity of a geyser. The pressure in the chamber after an eruption is influenced by the atmospheric pressure. If the atmospheric pressure decreases, the pressure in the chamber after an eruption also decreases. Because of this, the inflow rate of cold water to the chamber increases. As described earlier, an increase in the inflow rate of cold water shortens the duration of the cavern filling but it lengthens the duration of the pre-play stage and this in turn lengthens the interval between eruptions. An increase in atmospheric pressure gives the opposite effect.

(a) Atmospheric pressure = 1.01325 bar (interval between eruptions = 1000 s)

(b) Atmospheric pressure = 1 bar (interval between eruptions = 1100 s)

Figure 6.30 Sensitivity of geyser performance to changes in the atmospheric pressure.
6.4.8. Porosity of the cold recharge zone

The sensitivity of geyser performance to change in the porosity of the recharge block was investigated by varying the porosity from 0.2 to 0.4. Due to the time constraint, however, only less than ten cycles were simulated in each case. In the short term, changes in porosity of the recharge zone has no effect on geyser performance (see Fig. 6.31). In the long term, however, a decrease in the porosity may cause a rapid pressure drop in the recharge zone resulting in a decrease in the inflow rate of cold water to the chamber and hence a decrease in the interval between eruptions. As has been shown in the MULKOM model (previously discussed in section 6.2.2), the interval between eruptions become shorter and shorter as the pressure in the recharge zone decreases.

![Graph showing sensitivity of geyser performance to changes in porosity.](image)

*Figure 6.31 Sensitivity of geyser performance to changes in the atmospheric pressure.*

6.4.9. Size of the vent

Three cases are compared in Table 6.7 in order to study how the performance will be affected by changes in the size of the vent. In the first two cases, the vent has the same diameter throughout the depth (called here single diameter vent) of 0.10 m² and 0.12 m² respectively. In the third case, the vent has a diameter of 0.10 m² down to 4 m depth and from 4 m to 10 m depth it has a diameter of 0.12 m² (called here a stepped diameter vent).

The model shows that changes in the size of the vent will affect the eruption rate and the interval between eruptions as well as the duration of the quiet stage and the duration of the pre-play stage. For the first two cases, for example, a decrease in the size of the vent by 17% (from
0.12 m² to 0.10 m²) increases the maximum eruption rate by 9% and the interval between eruptions by 4%. The duration of the quiet stage and the duration of the pre-play stage decreases by 11% and 3% respectively but the duration of the eruption and the duration of the falling stage remains constant. The third case gives results between the values for the first two cases, suggesting an averaging effect of the stepped diameter.

Table 6.7
The sensitivity of geyser performance to changes in the size of the vent.

<table>
<thead>
<tr>
<th></th>
<th>Single diameter vent&lt;sup&gt;1)&lt;/sup&gt;</th>
<th>A=0.10 m²</th>
<th>A=0.12 m²</th>
<th>A stepped diameter vent&lt;sup&gt;2)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of the falling stage (s)</td>
<td>40</td>
<td>40</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Duration of the quiet stage (s)</td>
<td>160</td>
<td>180</td>
<td></td>
<td>170</td>
</tr>
<tr>
<td>Duration of the pre-play stage (s)</td>
<td>1020</td>
<td>1050</td>
<td></td>
<td>1050</td>
</tr>
<tr>
<td>Duration of the eruption stage (s)</td>
<td>130</td>
<td>130</td>
<td></td>
<td>130</td>
</tr>
<tr>
<td>Maximum eruption (kg/s)</td>
<td>17.4</td>
<td>19.2</td>
<td></td>
<td>18.0</td>
</tr>
<tr>
<td>Maximum heat flow rate (MW)</td>
<td>9</td>
<td>10</td>
<td></td>
<td>9.5</td>
</tr>
<tr>
<td>Duration of the cavern filling (s)</td>
<td>200</td>
<td>220</td>
<td></td>
<td>210</td>
</tr>
<tr>
<td>Interval between eruption (s)</td>
<td>1220</td>
<td>1270</td>
<td></td>
<td>1260</td>
</tr>
</tbody>
</table>

1) *The vent has the same diameter throughout the depth.*
2) *The vent has a diameter of 0.10 m² down to 4 m depth and of 0.12 m² from 4 m to 10 m depth.*

6.4.10. Relative permeability curves

Relative permeabilities to water (k<sub>RL</sub>) and steam (k<sub>RV</sub>) are important parameters for the development of a fully transient model of a geyser because most of the time the cavern is occupied by water and steam. As was mentioned earlier, there is considerable uncertainty as to whether the relative permeability curves for porous media (e.g. Corey relative permeability curves) apply to fractures as well as to caverns larger than fractures. As early investigators suggest that the relative permeability curves for fractures differ from that generally accepted for porous media (see section 6.1), in the early study using MULKOM simulator they were treated as adjustable parameters (section 6.2). Because in the MULKOM model the Corey relative permeability curves with S<sub>LR</sub>= 0.0 and S<sub>VR</sub>= 0.3 (see Fig. 6.3) can sustain longer oscillatory discharge behaviour than that with S<sub>LR</sub>= 0.3 and S<sub>VR</sub>= 0.05 (the most common values used for porous media), the former relative permeability curves have been used in all experiments using the AUTOUGH2 simulator. This section discusses the results of some experiments using the Corey relative permeability curves but with different values for S<sub>LR</sub> and S<sub>VR</sub>.
Case 1: $S_{LR} = 0.10$ and $S_{VR} = 0.30$

In this case $S_{VR}$ is the same as that in the base case but $S_{LR}$ is 0.10 greater. $S_{LR} = 0.10$ and $S_{VR} = 0.3$ mean that the liquid phase becomes immobile when the liquid saturation is 0.10 and the steam phase become immobile when the steam saturation is 0.30. As can be seen in Fig. 6.32, increasing $S_{LR}$ has the effect of lowering the relative permeability to water ($k_{RL}$) but increasing the relative permeability to steam ($k_{RV}$). The result of simulations, summarised in Table 6.8, shows that there is no significant different in the performance of the geyser between case 1 and the base case. However, reducing $k_{RL}$ has the effect of decreasing the mobility of water ($k_{RL}/\mu_L$) resulting in a lower eruption rate. A higher $S_{LR}$ also causes the volume of the residual water after an eruption to become larger resulting in a shorter duration of the cavern filling. It also causes the inflow rate of cold water to be slightly smaller. This in turn causes the cavern temperature to rise more rapid result in a shorter duration of the pre-play stage. The interval between eruption thus decreases as $S_{LR}$ increases.

\[ \text{Figure 6.32 Relative permeability of water and steam as a function of liquid saturation.} \]

\[ \text{Table 6.8} \]

The sensitivity of geyser performance to $S_{LR}$ ($S_{VR} = 0.30$)

<table>
<thead>
<tr>
<th></th>
<th>$S_{LR}=0.0$ (base case)</th>
<th>$S_{LR}=0.10$ (case 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of the falling stage (s)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Duration of the quiet stage (s)</td>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>Duration of the pre-play stage (s)</td>
<td>770</td>
<td>760</td>
</tr>
<tr>
<td>Duration of the eruption stage (s)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Maximum eruption (kg/s)</td>
<td>17.5</td>
<td>17.2</td>
</tr>
<tr>
<td>Maximum heat flow rate (MW)</td>
<td>9.1</td>
<td>8.9</td>
</tr>
<tr>
<td>Duration of the cavern filling (s)</td>
<td>230</td>
<td>220</td>
</tr>
<tr>
<td>Interval between eruption (s)</td>
<td>1000</td>
<td>980</td>
</tr>
</tbody>
</table>
Case 2: $S_{LR} = 0.10$ and $S_{VR} = 0.20$

In case 2 $S_{LR}$ is the same as that in the case 1 but $S_{VR}$ is 0.10 less. In this case the liquid phase becomes immobile only when the liquid saturation is 0.10 and the steam phase become immobile when the steam saturation is 0.2. As can be seen in Fig. 6.33, decreasing ($S_{VR}$) also has the effect of lowering $k_{RL}$ and increasing $k_{RV}$. In case 2, however, $k_{RL}$ is much smaller but $k_{RV}$ is only slightly higher. Mobility of water ($k_{RL}/\mu_L$) is thus much smaller but the mobility of steam ($k_{RV}/\mu_V$) is only slightly larger. With such rock-fluid properties, the numerical model predicts that in the case 2 the maximum eruption will be much smaller but the duration of the eruption will be the same (see Table 6.9). Hence, the volume of residual water will be larger and a shorter time will be required to fill the cavern (see Figs. 6.34 and 6.11a and also Table 6.8 for comparison).

![Figure 6.33 Relative permeability of water and steam as a function of liquid saturation.](image)

**Table 6.9**

The sensitivity of geyser performance to changes in $S_{VR}$ ($S_{LR} = 0.10$)

<table>
<thead>
<tr>
<th></th>
<th>$S_{VR} = 0.3$ (case 1)</th>
<th>$S_{VR} = 0.20$ (case 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of the falling stage (s)</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Duration of the quiet stage (s)</td>
<td>180</td>
<td>160</td>
</tr>
<tr>
<td>Duration of the pre-play stage (s)</td>
<td>720</td>
<td>690</td>
</tr>
<tr>
<td>Duration of the eruption stage (s)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Maximum eruption (kg/s)</td>
<td>17.2</td>
<td>15.5</td>
</tr>
<tr>
<td>Duration of the cavern filling (s)</td>
<td>220</td>
<td>210</td>
</tr>
<tr>
<td>Interval between eruption (s)</td>
<td>980</td>
<td>900</td>
</tr>
</tbody>
</table>
Case 3: $S_{LR} = 0.30$ and $S_{VR} = 0.05$

In the third case, $S_{LR}$ and $S_{VR}$ are put equal to the most commonly used values for porous media (Fig. 6.3). Figs. 6.35 to 6.38 compare the mass discharge, the pressure in the chamber, the inflow rate and the steam saturation in the chamber versus time respectively, as predicted by the model for the base case and for case 3. In case 3 the water phase becomes immobile when the water saturation is 0.30 and the steam phase becomes immobile when the steam saturation is 0.05. From Fig. 6.3, $k_{RL}$ (and the mobility of water) is much smaller but $k_{RV}$ (and the mobility of steam) is much greater than those in the base case. For this reason, in case 3 the surface discharge is smaller and the volume of the residual water is greater resulting in a higher cavern pressure and a lower cold inflow than the base case. In the case 3 the volume of the residual water after an eruption is greater compared to the base case, so the duration of the cavern filling will be shorter and the duration of the pre-play stage is shorter because the inflow rate of cold water is smaller. Hence the cavern temperature rises at a faster rate and less time is required to bring water in the chamber to boiling.

A number of simulations were also carried out using different values of permeability for the channel and the chamber. The results, which are summarised in Fig. 6.39, show a similar trend to the base case results, obtained using $S_{LR} = 0.0$ and $S_{VR} = 0.3$. 

![Figure 6.34 Mass flow rate discharge to the atmosphere versus time for the case of $S_{LR}=0.10$ and $S_{VR}=0.2$ (case 1)](image)
(a) $S_{LR} = 0.0$ and $S_{LR} = 0.3$

(a) $S_{LR} = 0.0$ and $S_{LR} = 0.3$

(b) $S_{LR} = 0.3$ and $S_{LR} = 0.05$

Figure 6.35 Mass flow rate discharge to the atmosphere versus time for the case of $S_{LR} = 0.0$ and $SVR = 0.30$ (base case) and of $S_{LR} = 0.3$ and $SVR = 0.05$ (case 3).
Figure 6.36 Pressure in the chamber versus time for the case of $S_{LR} = 0.0$ and $S_{VR} = 0.30$ (base case) and of $S_{LR} = 0.3$ and $S_{VR} = 0.05$ (case 3).
(a) $S_{LR} = 0.0$ and $S_{LR} = 0.3$

(b) $S_{LR} = 0.3$ and $S_{LR} = 0.05$

Figure 6.37 Inflow rate of cold water to the chamber versus time for the case of $S_{LR} = 0.0$ and $SV_R = 0.30$ (base case) and of $S_{LR} = 0.3$ and $SV_R = 0.05$ (case 3).
(a) $S_{LR} = 0.0$ and $S_{LR} = 0.3$

(b) $S_{LR} = 0.3$ and $S_{LR} = 0.05$

Figure 6.38 Steam saturation in the chamber versus time for the case of $S_{LR} = 0.0$ and $S_{VR} = 0.30$ (base case) and of $S_{LR} = 0.3$ and $S_{VR} = 0.05$ (case 3).
Figure 6.39 Sensitivity of geyser performance to changes in relative permeability curves
6.5. Summary

The present study has shown that fully transient models of geysers can be set up using a numerical approach. The model results agree reasonably well with the analytical solutions and experimental data. The model provides some insight into the processes inside the system as a whole and give a quantitative picture of the surface discharge which is qualitatively similar to what has been observed in natural geysers, i.e. a steam phase (quiet period) follows the cessation of the eruption; water overflows from the channel, accompanied by intermittent splashes of boiling water or several modes of eruptions before a full column eruption. The model is also able to simulate the eruption process itself which cannot be modelled using the simple mathematical models.

The models show that the chamber and the channel are being filled with water during the quiet stage. The heating process takes place during the overflowing stage, and vigorous boiling occurs in the chamber during an eruption. The intermittent discharge behaviour prior to eruption is the result of flashing in the channel when the water temperature is higher than the boiling point.

The results of the sensitivity study discussed here give quantitative information on how the activity of a geyser is likely to be affected by changes in permeability, changes in the size of the vent, and changes in the inflow rate, pressure and temperature. The result of the sensitivity study can be summarised as follows:

(i) Changes in permeability of the channel and the chamber will have a significant effect on the eruption rate, as well as on the surface discharge during the pre-play stage and on the duration of eruption, but it has little effect on the interval between eruptions.

(ii) Changes in the rate and temperature of the hot inflow are always coupled with changes in the cold inflow. A decrease in the rate and temperature of the hot inflow will stimulate the cold inflow to the chamber resulting in a much longer interval between eruptions.

(iii) Recharge is an important element in geysers and has a strong effect on the interval between eruptions as well as on the duration of cavern filling (duration of the falling stage and the duration of the quiet stage) and the duration of the pre-play stage, but it has little effect on the eruption rate.

(iv) Changes in the ambient temperature will not significantly alter the geyser performance.

(v) Changes in atmospheric pressure may have a significant effect on the geyser performance.
(vi) The performance of the model of the geysers are strongly dependent on the relative permeabilities to water and steam.

This study has shown that fully numerical simulation using MULKOM and AUTOUGH2 provides a very useful tool for studying the performance of a geyser.