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MODELLING OF GEYSERS

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ABSTRACT

Geysers that discharge water and steam intermittently to the atmosphere are one of the rarest natural phenomena associated with geothermal systems. Several approaches including laboratory experiments, field observations and mathematical and numerical modelling studies are used in the present study to explain the behaviour of geysers and the important parameters controlling the eruption of geysers. A particular study is made of three geysers at Rotorua geothermal field: Pohutu, Prince of Wales Feathers and Waikorohihi.

The existing mathematical model (Steinberg et al., 1981a) is studied and an improved mathematical model is developed to accommodate two-phase flow and the variation in fluid properties with temperature. Both the existing and the improved mathematical models are used to model Pohutu and are able to reproduce not only the interval between eruptions but also the durations of the cavern filling and the duration of the pre-play stage observed by the author on the 20th of August 1993.

Fully transient numerical models, which include the eruption process itself, are developed using MULKOM and the AUTOUGH2 simulators and produce reasonably good agreement with the analytical solutions and experimental data. The model provides information about the processes inside the geyser system and models the surface discharge which cannot be modelled using the Steinberg type of model. A fully transient model for Pohutu, which is developed using the AUTOUGH2 simulator, is able to reproduce the behaviour observed by the author on the 20th of August 1993.

The results of sensitivity studies show that of the three Rotorua geysers, the Feathers is the most sensitive to changes in the rate of the hot upflow from depths. Both the Feathers and Waikorohihi are more sensitive to temperature changes than Pohutu. Pohutu is currently a vigorous geyser with preliminary pulsating spring behaviour; large changes in the rate and temperature of the hot upflow would be required to stop it erupting. All geysers are sensitive to variations in the water level and temperature in Te Horu.
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NOTATIONS AND SYMBOLS

A = cross sectional area (m²)
A_L = cross sectional area occupied by the liquid phase (m²)
A_{eff} = effective area of the vent (m²)
c = specific heat (kJ/kg.K)
c_h = specific heat of hot water (kJ/kg.K)
c_c = specific heat of cold water (kJ/kg.K)
c_p = specific heat of water in the chamber (kJ/kg.K)
c_r = specific heat of rock (kJ/kg.K)
Cl^i = chloride concentration of the erupted water when first ejected (ppm)
Cl^f = chloride concentration of the erupted water at the end of eruption (ppm)
d = diameter of the chamber (m)
d_h = diameter of the channel (m)
d_{t1} = duration of the chamber filling (s)
d_{t1a} = actual duration of the chamber filling (s)
d_{t2} = duration of the channel filling (s)
d_{t2'} = duration of the channel filling+duration of the heating up for non-overflowing geyser (s)
d_{t3} = duration of the heating up until eruption (s)
d_{tcr} = interval between eruptions (s)
d_{twp} = duration of the water play (s)
d_p = duration of eruption for Pohutu (s)
d_r = duration of eruption for the Feathers (s)
d_w = duration of eruption for Waikorohihi (s)
E = energy contained in the fluid (kJ)
E_0 = energy contained in the residual water (kJ)
E_{twp} = energy contained in the fluid at the beginning of the chamber filling (kJ)
E_c = energy transferred to the system by the cold water (kJ)
E_d = energy losses carried by the overflowing water (kJ)
E_h = energy transferred to the system by the hot water (kJ)
E_q = energy input to the system (kJ)
E_p = eruption rate for Pohutu (kg/s)
E_f = eruption rate for the Feathers (kg/s)
E_w = eruption rate for Waikorohihi (kg/s)
F_1 = function of the liquid viscosity number (N_L)
\[ F_2 = \text{function of the liquid viscosity number (N}_f \text{)} \]
\[ F_3 = \text{function of the liquid viscosity number (N}_f \text{)} \]
\[ F_4 = \text{function of the liquid viscosity number (N}_f \text{)} \]
\[ F_5 = \text{function of the liquid viscosity number (N}_f \text{)} \]
\[ F_6 = \text{function of the liquid viscosity number (N}_f \text{)} \]
\[ F_7 = \text{function of the liquid viscosity number (N}_f \text{)} \]
\[ g = \text{acceleration due to gravity (m}^2\text{/s)} \]
\[ G = \text{total inflow of cold and hot water entering the chamber (kg/s)} \]
\[ G_L = \text{mass flow rate of the liquid (kg/s)} \]
\[ G_S = \text{mass flow rate of the steam (kg/s)} \]
\[ G_1 = \text{total inflow of cold and hot water during stage-1, the chamber filling (kg/s)} \]
\[ G_2 = \text{total inflow of hot and cold water at the end of stage-2 (kg/s)} \]
\[ G_C = \text{mass flow rate of cold water entering the chamber (kg/s)} \]
\[ G_{C0} = \text{mass flow rate of cold water after an eruption, i.e. at initial condition (kg/s)} \]
\[ G_{C1} = \text{mass flow rate of cold water during stage-1, the chamber filling (kg/s)} \]
\[ G_{C2} = \text{mass flow rate of cold water at the end of stage-2 (kg/s)} \]
\[ H_L = \text{liquid hold up} \]
\[ H_G = \text{void fraction} \]
\[ H = \text{length of the channel (m)} \]
\[ H_{\text{plume}} = \text{height of eruption (m)} \]
\[ h = \text{enthalpy of the fluid (kJ/kg)} \]
\[ h_d = \text{enthalpy of the overflowing water (kJ/kg)} \]
\[ h_f = \text{enthalpy of the liquid phase (kJ/kg)} \]
\[ h_g = \text{enthalpy of the vapour phase (kJ/kg)} \]
\[ h_{fg} = \text{heat of vaporization (kJ/kg)} \]
\[ h_{fc} = \text{enthalpy of the cold water (kJ/kg)} \]
\[ h_{fh} = \text{enthalpy of the hot water (kJ/kg)} \]
\[ h_0 = \text{enthalpy of the residual water after an eruption (kJ/kg)} \]
\[ K = \text{effective conductivity of the rock} \]
\[ k = \text{absolute permeability of the rock} \]
\[ k_{RL} = \text{relative permeability to liquid} \]
\[ k_{RV} = \text{relative permeability to vapour} \]
\[ L = \text{length of the chamber (m)} \]
\[ L_i = \text{length of water column (m)} \]
\[ L_B = \text{bubble-slug boundary, dimensionless} \]
\[ L_S = \text{slug-transition boundary, dimensionless} \]
L_M = transition-mist boundary, dimensionless
L_1 = function of the pipe diameter number (N_D)
L_2 = function of the pipe diameter number (N_D)
M = mass of the fluid in the system (kg)
M_0 = mass of the residual water after an eruption (kg)
N = mass at the beginning of the chamber filling (kg)
M_c = mass of cold water flowing into the system (kg)
M_d = mass of the fluid leaving the system (kg)
M_h = mass of hot water flowing into the system (kg)
N_GV = dimensionless gas velocity number
N_LV = dimensionless liquid velocity number
N_D = dimensionless pipe diameter number
N_L = dimensionless liquid viscosity number
N_Reb = Reynold number of the bubble
N_ReL = Reynold number of the liquid
S = dimensionless slip velocity
P = pressure (Pa)
P_0 = pressure in the cold water zone (Pa)
P_a = atmospheric pressure (Pa)
P_b = pressure at the bottom of the channel (Pa)
P_0 = pressure in the chamber after an eruption, i.e. at the initial condition (Pa)
P_1 = pressure in the chamber during stage-1, the chamber filling (Pa)
P_2 = pressure in the chamber at the end of stage-2, the channel filling (Pa)
Q_m = heat input to the chamber (kW)
R_P = Inflow rate of hot water for Pohutu (kg/s)
R_f = Inflow rate of hot water for the Feathers (kg/s)
R_W = Inflow rate of hot water for Waikorohihi (kg/s)
S_L = saturation of liquid
S_V = saturation of vapour
S_LR = residual saturation of liquid
S_VR = residual saturation of vapour
S = cross section area of the channel (m^2)
s = entropy of water at cavern temperature (kJ/kg)
s_s = entropy of the steam phase at 100°C
s_w = entropy of the water phase at 100°C
t = time (seconds)
t_0 = time when the simulation started (s)
t_1 = time at the end of stage-1, i.e. end of the chamber filling (s)
\[ t_2 \] = time at the end of stage-2, i.e. end of the channel filling(s)
\[ t_3 \] = time at the end of stage-3, i.e. time when an eruption occurs (s)
\[ t_p \] = interval between eruptions for Pohutu (s)
\[ t_r \] = interval between eruptions for the Feathers (s)
\[ t_W \] = interval between eruptions for Waikorohihi (s)
\[ T \] = temperature (°C)
\[ T_c \] = temperature of cold water (°C)
\[ T_d \] = temperature of the overflowing water (°C)
\[ T_h \] = temperature of hot water (°C)
\[ T_s \] = saturation temperature (°C)
\[ T_0 \] = temperature of the residual water after an eruption, i.e. at the initial condition (°C)
\[ T_1 \] = temperature at the end of stage-1 (°C)
\[ T_2 \] = temperature at the end of stage-2 (°C)
\[ T_{ch1} \] = temperature of water in the chamber after an eruption (°C)
\[ T_{ch2} \] = temperature of boiling water at atmospheric pressure (°C)
\[ T_{eq1} \] = equilibrium temperature of the mixed hot and cold water during stage-1 (°C)
\[ T_{eq2} \] = equilibrium temperature of the mixed hot and cold water at the end of stage-2 (°C)
\[ T_{eq3} \] = equilibrium temperature of the mixed hot and cold water during stage-3 (°C)
\[ T_p \] = cavern temperature for Pohutu (°C)
\[ T_f \] = cavern temperature the Feathers (°C)
\[ T_W \] = cavern temperature Waikorohihi (°C)
\[ U_0 \] = nozzle velocity (m/s)
\[ V \] = volume of the water (m³)
\[ V_1 \] = volume of the water in the chamber at the end of stage-1 (m³)
\[ V_0 \] = volume of the residual water after an eruption (m³)
\[ V_t \] = volume of the chamber plus volume of the channel (m³)
\[ V_{ch} \] = volume of the channel (m³)
\[ V_{cb} \] = volume of the chamber (m³)
\[ V_M \] = mixture velocity (m/s)
\[ V_G \] = actual gas or steam velocity (m/s)
\[ V_L \] = actual liquid velocity (m/s)
\[ V_S \] = slip velocity (m/s)
\[ V_{SG} = \text{superficial gas or steam velocity (m/s)} \]
\[ V_{SL} = \text{superficial liquid velocity (m/s)} \]
\[ V_{B} = \text{bubble rise velocity (m/s)} \]
\[ W_{L} = \text{water level in the channel (m)} \]
\[ W_{L0} = \text{water level after an eruption (m)} \]
\[ X_P = \text{Inflow rate of cold water for Pohutu (kg/s)} \]
\[ X_f = \text{Inflow rate of cold water for the Feathers (kg/s)} \]
\[ X_w = \text{Inflow rate of cold water for Waikorohihi (kg/s)} \]
\[ \chi = \text{steam quality in the mixture} \]
\[ \alpha = \text{recharge parameter (m.s)} \]
\[ \rho = \text{density (kg/m}^3) \]
\[ \rho_0 = \text{density of the residual water after an eruption (kg/m}^3) \]
\[ \rho_G = \text{density of steam (kg/m}^3) \]
\[ \rho_V = \text{density of steam (kg/m}^3) \]
\[ \rho_L = \text{density of liquid water (kg/m}^3) \]
\[ \rho_r = \text{density of rock (kg/m}^3) \]
\[ \rho_w(T) = \text{density of water at cavern temperature (kg/m}^3) \]
\[ \rho_w(100^\circ\text{C}) = \text{density of water at 100}^\circ\text{C (kg/m}^3) \]
\[ \mu_L = \text{viscosity of liquid water (kg/m.s)} \]
\[ \mu_G = \text{viscosity of steam or gas (kg/m.s)} \]
\[ \sigma = \text{liquid surface tension (dynes/cm)} \]
\[ \Delta t = \text{time increment (s)} \]
\[ \phi = \text{porosity} \]
\[ \lambda = \text{steam fraction of the total mass flux} \]
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