FLUID DYNAMICS DURING ERUPTION OF WATER-STEAM AND MAGMA-GAS SYSTEMS: GEYSERS, MAARS AND DIATREMES

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Expansion of a vapor phase in a multicomponent, multiphase system controls the fluid flow characteristics during eruption of geysers, maars and diatremes. In geyser eruptions the multiphase fluid is a water-steam or, rarely, a water-carbon dioxide mixture; in maars and diatremes the fluid may be as simple as a water-steam mixture, or may be a complex mixture of magma, water and/or carbon dioxide. Geysers are considered here as analogues of maars and diatremes because they are readily available for observation, because there are sufficient equation-of-state data on water that quantitative results and predictions can be obtained, and because geysers exhibit many patterns of eruption which should be common to thermodynamically similar mixtures erupted from greater depths. In this paper an analytic model of flow of two-phase systems (water-steam; water-carbon dioxide; and albite-water) is used to study eruption dynamics and to predict observed surface eruption patterns of geysers. In the eruption model, a liquid phase, initially undersaturated in volatiles at all depths except possibly near the top of the fluid column (Figure 1) is assumed to begin eruption instantaneously when the surface is unloaded (Figure 2), e.g., when surface fluid overflows or when a crack is propagated to the surface. The fluid flow equations of conservation of mass, momentum, and energy, supplemented by an equation of state for the fluid, are solved by the method of characteristics. The motions of the disturbance waves and the fluid surface are shown schematically in Figures 2 - 5. The initial unloading disturbance propagates down the fluid column as an unloading (rarefaction) wave ($R_1(-)$ in Figure 3) that accelerates the fluid out of the conduit; the motion of the fluid surface is shown as D_1 in Figure 3. The velocity of ejection of the fluid is proportional to the sound speed of the fluid which, in turn, depends on the composition, pressure, temperature, vapor fraction, bubble size, surface tension, and on whether or not thermal equilibrium is maintained between the liquid and gas phases during the eruption (Figure 6). The sound speed of a liquid-gas mixture is typically two to three orders of magnitude lower than the sound speed of the pure liquid end member and one order of magnitude lower than the pure vapor end member; it is a few meters per second for water-steam mixtures at 100°C.

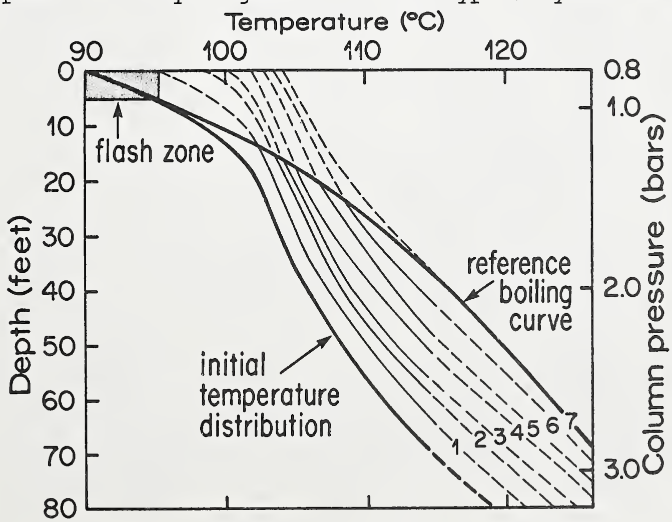


Figure 1. Initial temperature distribution in Old Faithful taken 15 seconds before eruption (Birch and Kennedy, 1972) compared to reference boiling curve at elevation of Yellowstone National Park. Curves 1-7 explained in text.

Figure 2.

Time: immediately prior to eruption

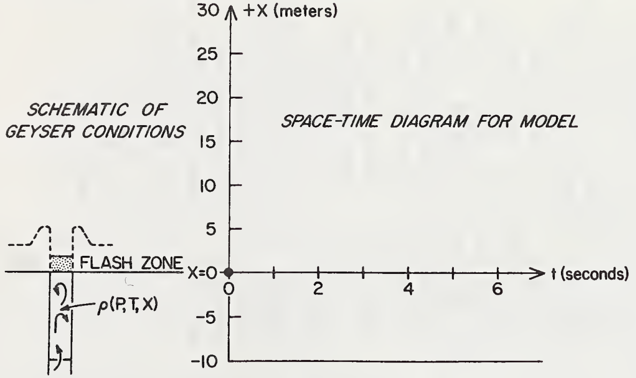


Figure 3.

Time: during ascent of column and descent of rarefaction into conduit

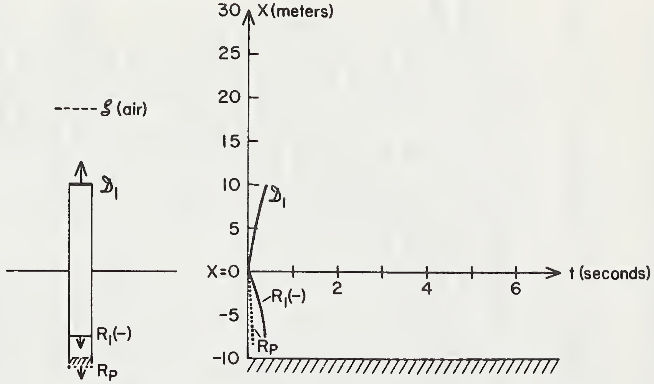


Figure 4.

Time: after column attains maximum height and begins descent

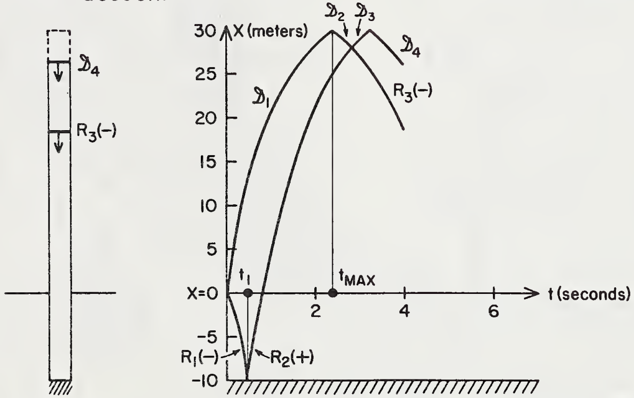
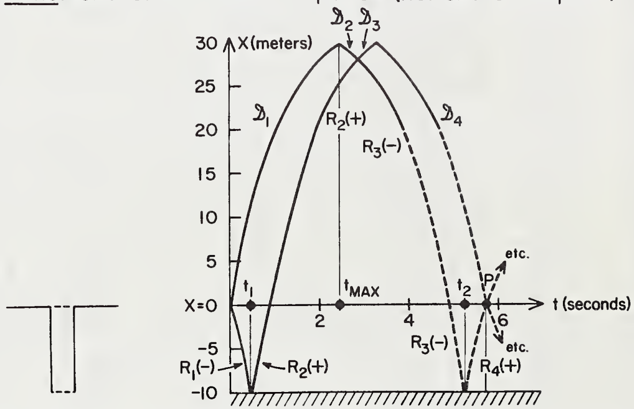
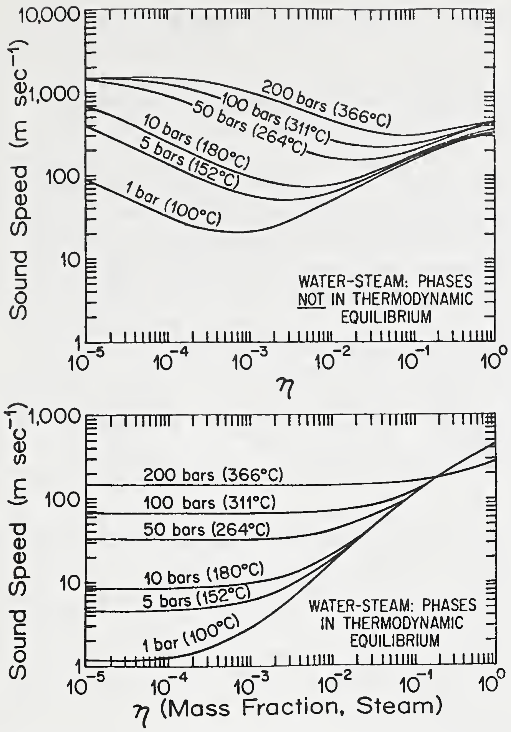


Figure 5.

Time: end of one staccato period (not end of eruption)



Figures 2,3,4,5. Schematic illustrations of propagation of initial unloading wave down a conduit containing a fluid which is initially below the reference boiling curve. In these drawings it is assumed that only 10 meters of the fluid can be brought to the boiling curve by the initial unloading disturbance; the bottom of this zone is modeled as a rigid wall--in reality it is the boundary between the two-phase zone developed by unloading and the single (liquid) phase at greater depths.



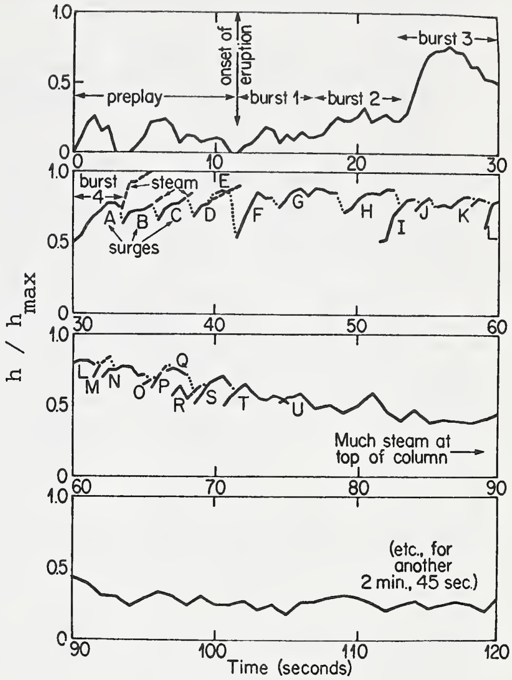


Figure 6 (left). Sound speed of water-steam mixture as a function of pressure and mass fraction steam. Figure 7 (right). The height of eruption of Old Faithful geyser normalized to the maximum height as a function of time. Nonsteady flow prevails from the onset of eruption through four bursts; steady flow prevails at later times.

The flow during an eruption is controlled by the sound speed of the fluid in the conduit as the rarefaction waves pass through it and is initially nonsteady flow which changes to steady flow only when the entire column of fluid has been brought to the saturation curve by a repeated series of staccato "bursts" of the kind shown in Figures 2-5. These bursts bring the column stepwise up to the boiling curve (see Figure 1 which shows seven such steps). The ejection velocity during nonsteady flow is characterized by these bursts which bring the eruption to its maximum height (Figure 7). The frequency of the bursts depends on the sound speed, on the depth of initial unloading, and on the temperature profile in the fluid at the onset of eruption. The duration of the nonsteady flow phase depends on the degree to which the initial temperature profile departs from the saturation curve: it is very short if the initial temperature profile lies near the saturation (or boiling) curve and long if it departs substantially from the saturation curve at depth. If the initial temperature profile is nearly isothermal at depth, steady state eruption conditions may never be reached and the entire eruption will be characterized by "bursts". The steady flow phase is characterized by relatively constant ejection velocities with small velocity variations which arise from organ pipe resonances (see Figure 7). In summary, the eruption of a two-phase system has a different character from the eruption of a single-phase system because the eruption dynamics are controlled by the kinetics and thermodynamics of expansion of a vapor phase within a multicomponent, multiphase system.