

Physics of thermohydraulic explosions

Ralf Büttner and Bernd Zimanowski*

Physikalisch-Vulkanologisches Labor, Institut für Geologie, Universität-Würzburg, Germany

(Received 14 November 1997)

We propose a phenomenological model for explosive water-melt interactions. Thermohydraulic fracturing was experimentally identified to be the main contributor to explosive energy release. We found experimental evidence that the model is applicable for a variety of melt compositions with very different thermal and rheological properties. The proposed mechanism does not require special premixing conditions. The pre-explosive geometries yielding the most intensive explosions were found to be cm to dm sized water domains entrapped by excess melt. First approximations to the thermal to kinetic energy conversion ratio show that the identified process can explain the occurrence and the damage potential observed in industrial accidents and volcanic eruptions. [S1063-651X(98)02305-8]

PACS number(s): 62.10.+s, 44.60.+k, 62.20.Mk

I. INTRODUCTION

Intensive explosions can be observed during the contact of a hot liquid with a cool liquid, if the temperature of the hot liquid exceeds the homogeneous nucleation temperature of the coolant. This phenomenon was named the fuel-coolant-interaction (FCI) [1], respectively, “steam explosion” or “vapor explosion.” In the case of water and a hot melt the term molten-fuel-coolant-interaction (MFCI) has been introduced. Being a source of severe accidents in industrial plants MFCI has been intensively studied by physicists and engineers over the last 25 years. In volcanism MFCI was identified to play an important role in the course of explosive eruptions [2].

During MFCI a complex multiphase (in many cases also a multicomponent) system interacts under nonequilibrium thermodynamic conditions. Due to the multidisciplinary character of the involved research groups a variety of experimental approaches have been followed [3,4]: single melt droplets in water, melt jets in water, shock-tube configurations, prefragmented melt in water, stratification experiments, and entrapped water in melt. MFCI commonly is described in four phases: (phase 1) Hydrodynamic mixing of water and hot melt under stable vapor-film boiling conditions; (phase 2) induction and propagation of rapid breakdown of insulating vapor films; (phase 3) escalative heat transfer and superheating of water; and (phase 4) quantitative vaporization and system expansion.

In order to explain the high conversion ratio from thermal to kinetic energy, as deduced from experiments, accidents, and volcanic eruptions, some authors introduced a thermal detonation model [5,6], assuming a positive feedback mechanism which couples phase 2 and phase 3. This mechanism, however, would require a homogeneous premixture resulting from phase 1. In cases of high density melts, high viscosity

melts, low superheated melts, and especially in the case of a combination of these properties, the generation of a homogeneous premix becomes unlikely.

In this work we present experimental results, which identify a thermohydraulic process during phase 3 of MFCI (Sec. II). In Sec. III it is shown that this process is the main contributor of explosion energy. A model of MFCI is introduced in Sec. IV, which can explain the observed kinetic energy release without a thermal detonation mechanism. In Sec. V conclusions are given and implications are discussed.

II. EXPERIMENTS

In volcanism water and magma can form local mixes of cm to dm sized domains leading to highly energetic explosions [7]. Caused by the viscosity of magma (1 to 10^6 Pa s) and restricted differential flow speeds (< 20 m/s) hydrodynamic mixing of water and magma on such a scale requires a considerable time period (> 1 s). Magma is a subliquidus system and the typical overheat above solidus temperature rarely exceeds 150 K. Even if reduced heat transfer under stable film boiling conditions is assumed, cooling of the melt is so effective, that cm-sized magma domains dispersed in water will solidify completely in less than a second and MFCI will be hindered [8]. Therefore, explosive premixes of magma and water nearly exclusively form as dispersed water domains in excess melt (entrapment configuration). The findings presented here were obtained by performing mesoscale experiments in an entrapment configuration: test melts were prepared under atmospheric conditions in containments (dm-sized crucibles) within which then water was injected into the melt. Entrapment experiments were performed using silicate compositions (remelted volcanic rocks), ion melts (carbonates, sodium chloride), and metal melt (tin). A detailed description of the setup is given in [9].

In [10] premixing experiments with silicate melt have shown that the intensity of explosions depends on the initial water-melt ratio as well as on the differential flow speed (hydrodynamic mixing energy). Optimum premixes were found to be water domains with wavy surfaces with volumes of 10 to 20 ml dispersed in excess melt. These were produced by considerably low mixing energies (differential flow

*Author to whom correspondence should be addressed. Address correspondence to Physikalisch-Vulkanologisches Labor, Institut für Geologie, Universität-Würzburg, Pleicherwall 1, D-97070 Würzburg, Germany. FAX: +49-931-312378. Electronic address: zimano@rzbox.uni-wuerzburg.de

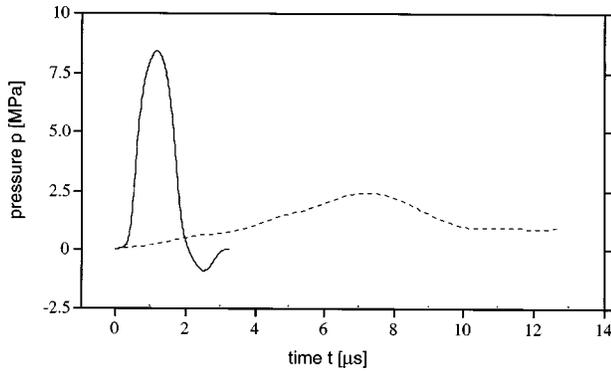


FIG. 1. Two pressure pulses (as examples) which were found to have the potency of triggering an explosive water/melt interaction.

speed 4.2 m/s) at low water-melt mass ratios (0.03–0.04). The explosion intensity was found to be proportional to the pre-explosive water-melt interface area. Thus, MFCI does not require a highly fragmented and homogeneous water-melt premix. Water mass flux per unit time was found to be of minor influence, at least in the investigated range. When water mixes with hot melt, thermally insulating vapor films form, which limit the heat flux between both media (Leidenfrost phenomenon). A quantitative collapse of these vapor films is a necessary condition for MFCI (phase 2). This collapse is experimentally achieved by application of trigger signals, i.e., pressure pulses respectively shock waves [11]. With the use of the experimental setup [9] we investigated the influence of wavelength and amplitude of the trigger signal onto the explosion intensity. A wide range of signals was found to have the quality of a trigger (see Fig. 1), i.e., to induce a complete vapor film collapse in a mesoscale premix in such a way, that direct contact of water and melt is established quasicoherently [12]. The explosion intensity, however, depended on the intensity of the triggering signal (see Fig. 2). Influences of size and shape of the containment were not observed.

Phase 3 of MFCI is characterized by escalative interface growth of the thermally and mechanically coupled system, caused by fine fragmentation on a μm scale [13]. The time

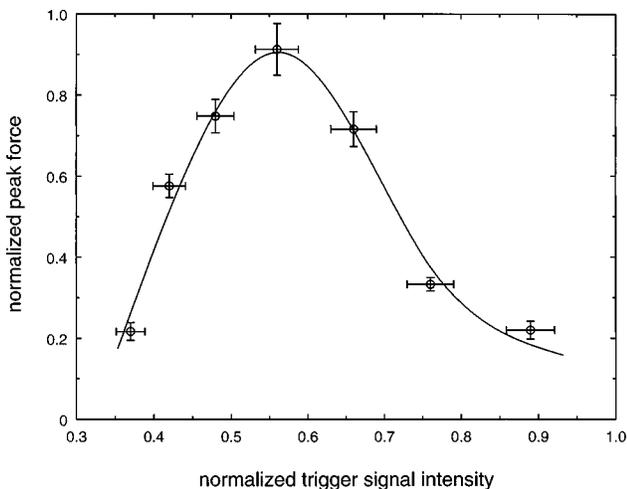


FIG. 2. Relationship between trigger energy and peak force component acting onto the container for the pressure pulse shown in Fig. 1 (dotted line) as an example.

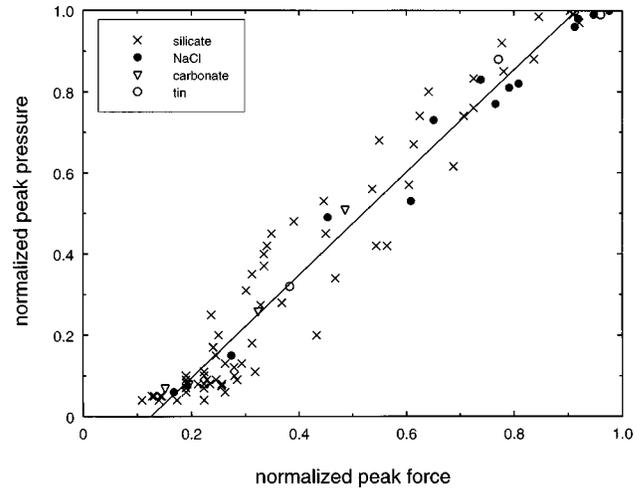


FIG. 3. Peak pressure of the explosion shock wave plotted versus the peak force component acting onto the container. The data not only reflects different melt compositions and temperatures (silicate melt: 1600 to 1700 K, carbonate melt: 1100 to 1150 K, salt melt: 1170 K, tin melt: 900 to 1100 K), but also various container (crucible) sizes and materials (ceramics, quartz glass, steel, metal ceramics).

scale of this phase was experimentally determined to be in the ms range. Using an appropriate melt composition, it was possible to identify and quantify the particles which were exclusively generated during this phase [9], thus representing the part of the melt which interacted thermally with water (i.e., interactive melt). The shape and size distribution of this particle population pointed to a brittle-type fragmentation process, that acted under extremely high cooling rates ($>10^6$ K/s). The total surface area of the particles generated during this brittle process has been determined and was found to be linearly proportional to the explosion intensity [14]. Such a behavior was also reported from other fracture experiments [15]. The brittle process was verified by specially designed experiments using high-speed cinematography, and two brittle mechanisms were identified [12]: (a) formation of leading cracks (mm to cm scale) due to excess water pressure, and (b) a slower, μm scaled melt fragmentation induced by strain build up in the melt during rapid cooling.

During phase 3 a major release of kinetic energy could be detected by (a) force transducers, elastically coupled to the containment, and (b) by pressure transducers in the surrounding air [9]. The mean signal speed in air (measured at a distance of 1.6 m) was $356(\pm 2)$ m/s, independent of the explosion intensity in the investigated range. This signal speed indicates a shock wave. The detected force signals (a) and pressure signals (b) show a linear proportionality, irrespective of (i) the locus of explosion in the containment; (ii) size, geometry, and yield strength of the containment, and (iii) melt composition (see Fig. 3). Furthermore, the optical records showed no detectable volume increase of the system during phase 3 [9], thus indicating a quasi-isochoric behavior.

If brittle-type fine fragmentation of the melt during phase 3 takes place, electrical effects resulting from contact electricity should be expected. Therefore, specially designed experiments were performed [14]. It was found that character-

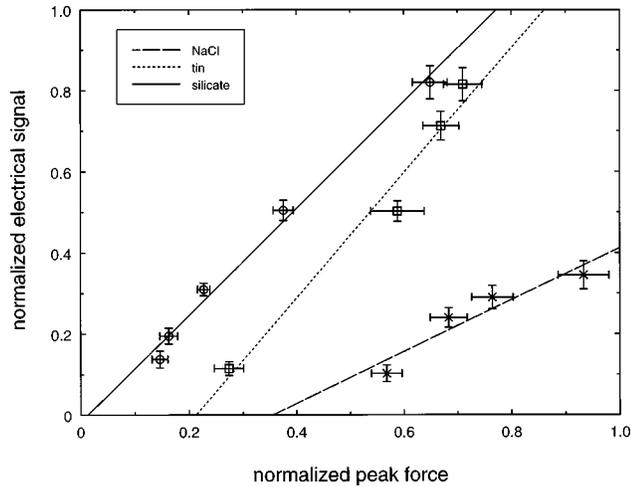


FIG. 4. Electrical signal plotted vs the peak force component acting onto the container for three melt compositions: metal melt, ion melt, and silicate melt.

istic electrical signals are produced during phase 3, which are linearly proportional to the explosion intensity and to the total surface area of the particles generated by the brittle process. Additional experiments using the identical setup [14] but other melt types also show linear proportionalities to the explosion intensity (see Fig. 4). The different slopes can be explained by specific material properties. The experimental results point to a brittle-type fragmentation mechanism with approximately spherical symmetry during phase 3 in all cases. It can be assumed, that the fragmentation mechanism described above is not only valid in the case of silicate melts and ion melts [9,12], but also in the case of metal melts.

The expansion phase (phase 4), in contrast to phases 1–3, could be observed directly using highspeed cinematography in [9]. The kinetic energy released during phase 4 represents only a minor part of the total energy release. The expansion history of experimental MFCI was simulated, substituting the driving superheated steam by pressurized inertial gas [9,14]. The driving pressures necessary to explain the observed bandwidth of experimental MFCI expansion phase was in the range of 5 to 15 MPa.

III. ENERGY CONSIDERATIONS

As a significant contribution of exothermal chemical reactions to the energy budget can be excluded in the experiments described above, the energy released during the explosions is delivered only by the thermal energy of the respective interactive melt. As shown in [9] the interactive melt mass can be determined with high precision in the case of the silicate test melt. The thermal properties of the composition used in the experiments were measured in [16]. The following energy considerations are based on the experimental data of explosions with (a) mean intensities and (b) high intensities, taken from [9].

The maximum thermal energy available (i.e., the thermal energy of the respective interactive melt mass [$T=1650$ K] assuming cooling to the initial water temperature ($T=290$ K]) was calculated for (a) to be 10.4 kJ and for (b) to be 27.9 kJ. For the calculation of the explosion shock wave energy the force transducer system was calibrated (using

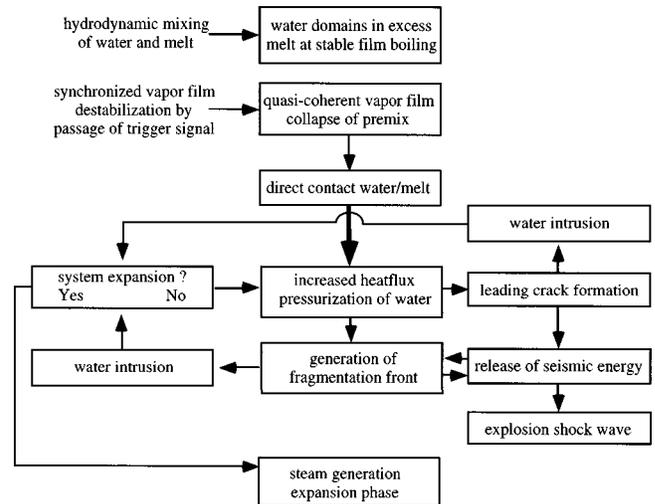


FIG. 5. Flow-chart diagram of the phenomenological model of thermohydraulic explosion.

shock waves of known energy). It was found to be in case (a) 1.5 kJ and in case (b) 8 kJ. The fragmentation energy consumed during phase 3 was calculated from the total surface area created, taken from [9]. Assuming a work of fracture for crack formation after [15] of 1 kJ/m^2 a fragmentation energy of approximately 2 kJ in case (a) and 4.9 kJ in case (b) was found. The kinetic energy release during the expansion (phase 4) was optically determined (see above) to be 0.5 kJ in case (a) and 0.7 kJ in case (b). Thus, the total kinetic energy release during the explosions was in case (a) 4 kJ and in case (b) 13.6 kJ. Now it is possible to estimate a minimum conversion ratio for the explosion mechanism: 38.5% in case (a) and 48.7% in case (b). These values, however, represent local conversion ratios taking into account only the interactive melt. Considering the thermal energy of the total melt volume used in the experiments minimum conversion ratios up to 2% result.

IV. EMPIRICAL MODEL

Based on the experimental results summarized above, a model of the MFCI explosion mechanism can be developed (see Fig. 5): If water contacts a melt of sufficiently high temperature (at system pressures well below the critical pressure of water) explosive mixtures of water domains in melt can form in the stable film boiling regime. Depending on the rheology of the melt, the interface enlargement is controlled by the supplied hydrodynamic mixing energy. The degree of mixing in respect to the explosivity is limited: At high mixing energy the vapor film breakdown will become asynchronous, due to increasing influence of hydrodynamic surface instabilities. In addition, the lifespan of the resulting smaller water domains will be shortened by the increased heat flux. Prolonged mixing time will cause significant vaporization of water and subcooling of the melt. Therefore, an optimum pre-explosive mixture exists with cm to dm sized water domains entrapped in excess melt. The energy of the resulting explosions is proportional to the pre-explosive water-melt interface area. The thermohydraulic explosion mechanism is triggered by the quasicohent collapse of the vapor films of the premix, synchronized by a pressure pulse (trigger signal).

The optimum trigger signals are shock waves, because of their supersonic qualities. Direct contact between water and melt results in thermal and mechanical coupling of both liquids: heat flux and speed of sound increase by 1–2 magnitudes. Due to system inertia and the large difference between the thermal expansion coefficients of water and melt, heating of the water and cooling of the melt (under quasi-isochoric conditions) causes local pressure increase within μs . If the load pressure onto the melt exceeds a critical value the melt reacts as a stressed solid body by the formation of cracks on a mm to cm scale. Pressurized water will quickly intrude into these cracks (leading cracks), increasing the contact area and thus the heat flux. Extremely high cooling rates of the melt in the vicinity of the interface lead to high thermally induced stresses during the fast approach of the glass transition temperature. Triggered by the seismic energy released during the formation of the leading cracks a second brittle-type fragmentation cycle is started on a μm to mm scale. A fragmentation front thus forms which expands into the surrounding melt following the propagation of the leading cracks at a considerably lower speed. Both fragmentation mechanisms lead to an escalative behavior of heat transfer thus generating a positive feedback mechanism. Relaxation of the stored structural energy in a short time period by these brittle processes causes the explosion shock wave which can be detected in the surrounding. This thermohydraulic mechanism is terminated once the system starts to expand. Vaporization of superheated water occurs and the system is thermally and mechanically decoupled. During the following expansion phase the superheated water vaporizes completely and the generated steam expands to ambient pressure, thus releasing kinetic energy.

V. CONCLUSIONS AND OUTLOOK

The experiments described above have shown that during the thermohydraulically induced brittle fragmentation and heat transfer phase the major part of the totally observed kinetic energy was released. The consequence of this brittle reaction was the generation of shock waves in the surrounding, representing a major damage potential of the experimentally generated molten-fuel-coolant interactions. Steam generation and expansion, however, delivered only about 10% of the totally observed kinetic energy, which also were released in a significantly longer time period. The commonly used term “steam explosion” does not reflect these observations. Therefore, in this work we propose “thermohydraulic explosion” for a more satisfying characterization of the phenomenon. The short time inflative surface area generation by thermohydraulic fragmentation causes a surface dominated heat transfer. Thus the thermal properties of the involved melts were of minor influence. Similar premix geometries resulted in similar explosion intensities irrespective of the melt composition. The experimental observations point to a general validity of the thermohydraulic mechanism for explosive molten-fuel-water interactions.

The crucial condition for hazardous explosions was found to be the synchronized direct contact between water and melt, leading to a thermal and mechanical coupling. A development of effective safety techniques thus should concentrate on the prevention of this situation. If the formation of a potentially explosive premix cannot be excluded, efforts should be made to reduce either the speed of sound in the system or the heat flux or both. Future research is recommended on the effects of large geometries, i.e., escalation or damping mechanisms in interacting premixes in the m range or larger.

-
- [1] D. J. Buchanan, *J. Phys. D* **7**, 1441 (1974).
 [2] S. A. Colgate and T. Sigurgeirsson, *Nature (London)* **244**, 552 (1973).
 [3] T. G. Theofanous, *Nucl. Eng. Des.* **155**, 1 (1995).
 [4] L. S. Nelson, P. M. Duda, G. Fröhlich, and M. Anderle, *J. Non-Equilib. Thermodyn.* **13**, 27 (1988).
 [5] S. J. Board and R. W. Hall, *Nature (London)* **245**, 319 (1975).
 [6] A. Sharon and S. G. Bankhoff, *Int. J. Heat Mass Transf.* **24**, 227 (1981).
 [7] K. H. Wohletz and R. G. McQueen, in *Explosive Volcanism: Inception, Evolution, and Hazards* (National Academy of Science Press, Washington, D.C., 1984), p. 158.
 [8] B. Zimanowski, G. Fröhlich, and V. Lorenz, *Nucl. Eng. Des.* **155**, 335 (1995).
 [9] B. Zimanowski, R. Büttner, V. Lorenz, and H.-G. Häfele, *J. Geophys. Res.* **102**, 803 (1997).
 [10] B. Zimanowski, R. Büttner, and V. Lorenz, *Bull. Volcanol. (Berlin)* **58**, 491 (1997).
 [11] D. F. Fletcher, *Nucl. Eng. Des.* **155**, 27 (1995).
 [12] B. Zimanowski, R. Büttner, and J. Nestler, *Europhys. Lett.* **38**, 285 (1997).
 [13] S. J. Board, C. L. Farmer, and D. H. Pool, *Int. J. Heat Mass Transf.* **17**, 331 (1974).
 [14] R. Büttner, H. Röder, and B. Zimanowski, *Appl. Phys. Lett.* **70**, 1903 (1997).
 [15] E. Sharon, S. P. Gross, and J. Fineberg, *Phys. Rev. Lett.* **76**, 2117 (1996).
 [16] R. Büttner, B. Zimanowski, J. Blumm, and L. Hagemann, *J. Volcanol. Geotherm. Res.* (to be published).