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Alternative Fragmentation Theory for a Melt Droplet

Hakan Papuccuoglu*
Faurecia Japan, Aichi 461-0005, Japan
and
Fahir Borak†
Yeditepe University, 34755 Istanbul, Turkey

An alternative fragmentation theory is suggested for the triggering stage of the steam explosion phenomenon. When model equations are solved under conditions of large-scale steam explosion experiments, the heat transfer coefficient is calculated as 25.1×10^6 W · m^{-2}K^{-1}. It is shown that fast steam production based on the mentioned heat transfer coefficient can lead to the occurrence of a shock wave, which is one of the necessary conditions to have a large-scale steam explosion.

Nomenclature

C_{dcm} = drag coefficient between the coolant and the melt
C_{dmb} = drag coefficient between the melt and the steam bubble
c = heat capacity
e = internal energy
h_{total} = total heat transfer coefficient (heat transfer by radiation included in convection term)
M_{system} = mass of the melt before the fragmentation plus mass of the steam penetrating into the melt
$\dot{m}_{steam}$ = time rate of change of steam mass penetrating into the melt
P = pressure
P_{st} = steam pressure
P_1 = freestream static pressure
R = radius of the imaginary cylindrical control volume
r_b = radius of the mushroom-type steam bubble
r_j = radius of the steam jet
r_m = radius of the melt droplet
T = temperature
t = time
u = velocity
u_b = velocity of the mushroom-type steam bubble
u_j = velocity of the steam jet penetrating into the melt
u_1 = velocity of the melt (or freestream velocity if the melt is considered stationary)
Y_j = jet penetration distance
ΔT = temperature difference between the heat transfer surfaces
η = dynamic viscosity
η_{steam} = viscosity of the steam
ρ = density
ρ_j = density of the steam jet
σ = surface tension

Introduction

EXPLOSIVE interaction of hot molten metal with a cold volatile liquid, commonly known as steam explosion, can be a concern for several industries. In particular, it constitutes a potential danger for the nuclear reactors where hundreds of tons of fuel at 3000 K and an abundance of water are present. If the melt temperature is high enough, a steam film covers the melt immediately when it contacts with the water in the case of an accident. While the melt temperature decreases, the steam film around it becomes unstable. Finally, the steam film collapses, allowing the water to have direct contact with the melt. This phenomenon is known as triggering, which initiates the subsequent stages of a large-scale steam explosion. A triggered melt droplet fragments due to a physical mechanism, which is not well known yet. Heat transfer from the fragmented melt particles to the surrounding water results in fast steam production. If the steam production is fast enough to create a propagation wave, other melt droplets may also be triggered. Finally, a considerable part of the whole mixture expands rapidly, resulting in damage to the surrounding structures.

The first noteworthy investigation of steam explosion was done by Long[1] in 1957. According to this classical investigation, rapid expansion of a small amount of water, which is trapped between the sinking molten metal and the bottom surface of the water pool, caused the molten metal to fragment, that is, triggered the explosion. The triggering stage and the fragmentation are the most complicated parts of a steam explosion. The sources of difficulties in understanding the phenomenon are the very small timescales, multiphase, multi-component, and highly turbulent flowfields. Although several researchers developed a number of fragmentation theories and evaluated experimental data,[2–6] questions arose concerning the validity of those models. Kim and Corradini[7] proposed that a coolant finger penetrates into the melt following the steam film collapse. According to their theory, evaporation and expansion of the coolant trapped in the melt results in the shattering of the upper layer. The same cyclic process, film collapse, coolant penetration, and upper layer shattering of the melt, continues until all of the melt is fragmented. However, it takes a certain period of time for the coolant to move along the penetration distance from the surface to the region somewhere in the melt. Because the melt temperature is above the spontaneous nucleation temperature of the coolant, as one of the necessary conditions to initiate triggering, the coolant will evaporate almost instantly when it contacts with the melt. Therefore, coolant penetration into the melt in the form of liquid is unlikely, according to the present authors.

In the present investigation, using large-scale steam explosion data, an alternative fragmentation theory is introduced that quantitatively explains the relationship between the heat transfer rate and the occurrence of the propagation shock wave. According to this theory, the coolant evaporates almost instantaneously when it contacts with the melt. By the use of the same experimental conditions of the large-scale steam explosion experiments done in the Assessment of Loads and Performance of Containment in Hypothetical Accident (ALPHA) facility of the Japan Atomic Energy Research

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*Project Coordinator, 2-9-34-3F, Higashi Sakura, Higashi-ku, Nagoya. Member AIAA.
†Professor and Dean, Faculty of Engineering and Architecture, 26 Agustos Yerlesimi, Kayisdagi.

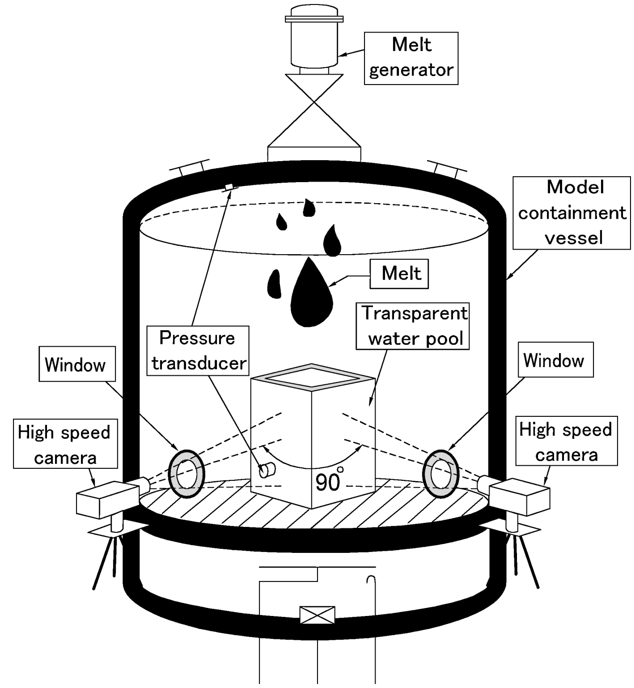

Fig. 1 ALPHA facility in JAERI, Japan.

Institute (JAERI),[8] model conservation equations are solved. It is shown that the consecutive steam production rate is high enough to create a shock wave, which is one of the necessary conditions to have a large-scale steam explosion.

Experimental Information

The volume, the height and the inner diameter of the ALPHA containment vessel are 50 m^3, 5.7 m, and 3.9 m, respectively. Its maximum pressure is 2 MPa, and the maximum melt generation capacity is 100 kg. It is possible to pressurize the containment vessel by using nitrogen. The facility has several windows to observe the experiments (Fig. 1). The melt generated by a thermite reaction of iron oxide and aluminum (before the reaction iron oxide 78 and aluminum 22, and after the reaction iron 58 and aluminum 42) is dropped in to the water pool made of acrylic resin. More information about the ALPHA facility of JAERI and the large-scale steam explosion experiments may be found in Refs. 8 and 9.

Fragmentation Model

The alternative fragmentation model suggested by the present authors consists of two parts. Those are hydrodynamic and thermal fragmentation models. In the former, only the hydrodynamic forces applied on the melt by the surrounding coolant are taken into consideration. In the thermal part of the theory, melt deformation due to the fast steam production is considered.

Fragmentation due to Hydrodynamic Forces

When the destabilized steam film around the melt collapses in a small region, direct contact of water with the melt leads to a sudden evaporation when the melt temperature is above the spontaneous nucleation temperature of the water. Local sudden evaporation acts as a propulsive force, such that it causes the melt and the steam film around the melt to accelerate in the surrounding water. The unstable steam film, which is vulnerable to outside disturbances, collapses in some other regions due to the hydrodynamic forces applied on the accelerated melt. Each subsequent film collapse and sudden local explosive evaporation will exert a propulsive force on the melt. Therefore, the melt will move in different directions randomly, depending on the random location of each subsequent film collapse and sudden local evaporation. Because the time difference between the two subsequent film collapses is expected to be small, the displacement of the melt in one direction under the effect of only one propulsive force should be small as well. In brief, the motion of the melt looks like a vibration, such that a bulk motion or a considerable displacement of the melt in one particular direction may not be observed. The motion of the melt and the hydrodynamic forces applied by the surrounding water will lead to deformation and fragmentation of the melt.

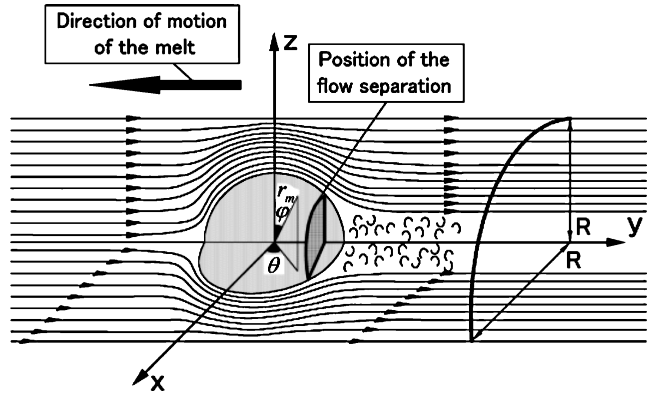

Fig. 2 Streamlines around the moving melt.

To set up an analytic model, which gives the hydrodynamic pressure distribution on the moving melt, the motion is analyzed in only one direction, that is, under the effect of one propulsive force. To simplify the equations, some assumptions are made. The melt is considered as a sphere, and its center is located on the axis of an imaginary cylindrical control volume of which the radius R is defined as the distance from the axis to the nearest undisturbed streamline (Fig. 2).

The motion of the melt in this control volume is assumed to be subsonic. The flow outside of the thin boundary layer formed around the melt is considered to be inviscid. The pressure just outside of the thin boundary layer is equal to the pressure on the melt surface. The conservation of mass equation is written for the imaginary cylindrical control volume,

$$R^2 \cdot \pi \cdot u_1 = \left[R^2 - r_m^2(1 - \sin^2\varphi \cdot \sin^2\theta)\right]\pi \cdot u \tag{1}$$

For the derivation of Eq. (1), see Fig. 2. The Bernoulli equation can be written for the streamline just outside the boundary layer as

$$P = P_1 + \left[\left(\rho_{\text{coolant}} \cdot u_1^2\right)/2\right] \times \left\{1 - \left[R^2 / \left(R^2 - r_m^2 + r_m^2 \cdot \sin^2\varphi \cdot \sin^2\theta\right)\right]^2\right\} \tag{2}$$

P gives the pressure distribution depending on φ and θ on the melt except in the region where the flow separation occurs. The pressure distribution seen in Fig. 3 is the qualitative illustration of Eq. (2). We consider that the unequal pressure distribution causes the melt to be deformed as shown in Fig. 3. At the foot of the deformed melt, total pressure (dynamic pressure plus static pressure) is comparatively high, depending on the velocity of the melt droplet. We think that if the total pressure-dependent forces at the foot of the deformed melt exceeds the surface tension forces, the deformed part of the melt can be broken up (Fig. 3). In brief, if the hydrodynamic destabilizing forces overcome the stabilizing surface tension forces, fragmentation starts. In the literature, there is some experimental evidence supporting the presently suggested theory such that the melt breakup takes place at the equator of the melt moving inside a surrounding fluid.[10]

Critical velocity can be calculated by means of the empirical relationship between Ohnesorge and critical Weber numbers for the gas liquid systems (see Ref. 11). If the original equation is rearranged, critical velocity can be expressed as

$$u_{\text{crit}}^2 = \frac{6 \cdot \sigma_{\text{melt}}}{\rho_{\text{coolant}} \cdot r_m}\left\{1 + 1.077\left[\frac{\eta_{\text{melt}}}{(\rho_{\text{melt}} \cdot 2r_m \cdot \sigma_{\text{melt}})^{0.5}}\right]^{1.6}\right\} \tag{3}$$

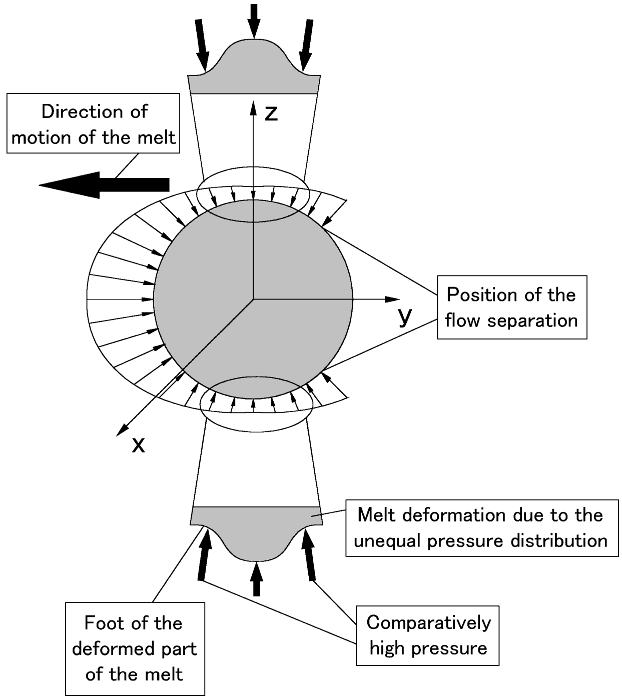

Fig. 3 Deformation of the melt due to uneven pressure distribution.

For the ALPHA large-scale steam explosion experiments,[8] $\sigma_{\text{melt}} = 0.5$ N/m, $\rho_{\text{melt}} = 3.62 \times 10^3$ kg/m^3, $T = 2700$ K, and $\eta_{\text{melt}} = 9.26 \times 10^{-5}$ Pa·s at $T = 2700$ K. (See the correlation proposed by Blomguist et al.[12] for the calculation of η_{melt}.) It is a reasonable assumption to accept the average melt radius as about 0.5 cm at the end of the premixing stage. When all of these values of ALPHA large-scale steam explosions are used, the critical velocity u_{crit} is found as 0.775 m/s. This velocity value, which indicates the maximum velocity of the melt just before the fragmentation stage, is used for the calculation of the heat transfer coefficient in the following thermal part of the theory.

Thermal Fragmentation Theory

Hydrodynamic forces applied on the moving melt by the surrounding coolant are not the only forces that cause the melt to be deformed. Because the melt is not a rigid body, small-scale explosive steam production in the region where the coolant contacts with the melt (triggering) will also cause the melt to be deformed. A steam finger penetrates into the melt forming a mushroom-type bubble (Fig. 4). Because the melt temperature is above the spontaneous nucleation temperature of the water, evaporation takes place in a very short period of time. There is a very small possibility that there will be two melt-water contacts in this very small time period. Therefore, conservation of mass, momentum, and energy equations are written for only one propulsive force due to one local explosive steam production.

$$\frac{\mathrm{d}M_{\text{system}}}{\mathrm{d}t} = \rho_j \frac{4}{3}\pi \cdot 3 \cdot r_b^2 \frac{\mathrm{d}r_b}{\mathrm{d}t} \tag{4}$$

Equation (4) is written for the instant just before the fragmentation starts. Therefore, $\mathrm{d}M_{\text{system}}/\mathrm{d}t$ is equal to the time rate of change of steam mass penetrating into the melt,

$$\frac{\mathrm{d}(M_{\text{system}} u_1)}{\mathrm{d}t} = C_{\text{dmb}} \frac{1}{2} \rho_{\text{melt}} (u_b - u_1)^2 \pi \cdot r_b^2 + \eta_{\text{steam}} \left. \frac{\mathrm{d}(u_j - u_1)}{\mathrm{d}r} \right|_{r=r_j} \times Y_j 2\pi r_j + P_{\text{st}} \cdot \left(\pi \cdot r_m^2 - \pi r_j^2\right) - C_{\text{dcm}} \frac{1}{2} \rho_{\text{coolant}} \cdot u_1^2 \cdot \pi \cdot r_m^2 \tag{5}$$

$$\frac{\mathrm{d}\left[\rho_{\text{melt}}(4/3) \cdot \pi \cdot r_m^3 \left(e + u_1^2/2\right)\right]}{\mathrm{d}t} = C_{\text{dmb}} \frac{1}{2} \rho_{\text{melt}} (u_b - u_1)^2 \pi \cdot r_b^2 u_1 + u_1 \eta_{\text{steam}} \left. \frac{\mathrm{d}(u_j - u_1)}{\mathrm{d}t} \frac{\mathrm{d}t}{\mathrm{d}r} \right|_{r=r_j} Y_j 2\pi r_j + P_{\text{st}} \cdot \left(\pi \cdot r_m^2 - \pi r_j^2\right) u_1 - C_{\text{dcm}} \frac{1}{2} \rho_{\text{coolant}} \cdot u_1^3 \cdot \pi \cdot r_m^2 - \left(4\pi \cdot r_m^2 + 4\pi \cdot r_b^2\right) \cdot h_{\text{total}} \Delta T \tag{6}$$

Of course, only a limited amount of the steam jet produced by local evaporation penetrates into the melt. Most of the steam expands into the surrounding coolant, which has surface tension and a density smaller than that of the melt. Some symbols used in Eqs. (4–6) are clarified in Fig. 4. Note that heat transfer by means of radiation is included in the heat transfer coefficient. The maximum (critical) value of $u_1 = u_{\text{crit}}$ is reached when $\mathrm{d}u_1/\mathrm{d}t = 0$. In Eq. (6), $\mathrm{d}e/\mathrm{d}t$ can be written as $\mathrm{d}(c \cdot T)/\mathrm{d}t$. When the mushroom-type steam bubble expands inside the melt, the time rate of chance of r_m is much smaller than that of r_b. Therefore, it is assumed that $\mathrm{d}r_m/\mathrm{d}t = 0$, compared to $\mathrm{d}r_b/\mathrm{d}t$ during the steam penetration into the melt. When Eqs. (4–6) are used, the following equation can be obtained:

$$u_{\text{crit}}^2 \rho_j \int r_b^2 \,\mathrm{d}r_b = \rho_{\text{melt}} \frac{1}{3} r_m^3 c \int \mathrm{d}T + r_m^2 h_{\text{total}} \Delta T \int \mathrm{d}t + h_{\text{total}} \Delta T \int r_b^2 \,\mathrm{d}t \tag{7}$$

Because triggering takes place in about 0.1 ms (Ref. 13), the integration limits should be taken from 0 to 0.1 ms for the second and third terms on the right-hand side of Eq. (7). It is assumed that when $r_b = r_m/2$, the melt will burst and disintegrate. Sensitivity of the results to this assumption will be evaluated in the uncertainty analysis. Radius r_b can be expressed as a function of time,

$$\rho_j \tfrac{4}{3}\pi \cdot r_b^3 = t \cdot \dot{m}_{\text{steam}} \Rightarrow r_b = 0.05386 \cdot t^{\frac{1}{3}} \tag{8}$$

Equation (8) is obtained for the case of $t = 0.1$ ms and $r_b = r_m/2 = \frac{1}{4}$ cm. Here $t = 0$ indicates the beginning of the triggering stage. Equation (8) is inserted in the last term of Eq. (7). The lower integration limit of the first term on the right-hand side of Eq. (7) is 2700 K, which is the initial temperature of the melt when it enters the water pool. At the instant when the melt breaks up into very small fragments, it is conventionally accepted that the heat is transferred from the melt to the coolant in a very short time such that melt, water, and the steam have the same temperature in the interaction region just after the triggering. During the ALPHA experiments, just after the fragmentation, the temperature and the pressure of the water suddenly rise to about 1500 K and 25 MPa, respectively. This temperature value is used as the upper integration limit of the first term on the right-hand side of Eq. (7). Steam density corresponding to those temperature and pressure values is about 13.601 kg/m^3. The heat capacity of the melt (iron alumina thermite mixture) used in the ALPHA experiments[8] is $c = 0.96 \times 10^3$ J/kg. The initial water temperature, before the melt is dropped into the pool, is about 300 K. Hence, $\Delta T = 2700 - 300 = 2400$. Equation (7) is solved using all of these values, and the heat transfer coefficient is found to be about $h_{\text{total}} = 25 \times 10^6$ W·m^{-2}K^{-1}.

Beside the hydrodynamic fragmentation mechanism explained in the first part, a continuously growing steam bubble inside the melt will eventually cause the melt droplet to burst and fragment. It is considered that fragmentation due to the hydrodynamic forces and thermal fragmentation occur simultaneously and interact with each other. Note that heat is not only transferred from melt to steam but also from melt to water during the fragmentation stage. The steam film around the melt is partially stripped off due to the melt movement as a result of local explosive steam production. Heat transfer between only steam and melt occurs in the expansion stage of steam explosion, which is beyond the scope of this paper.

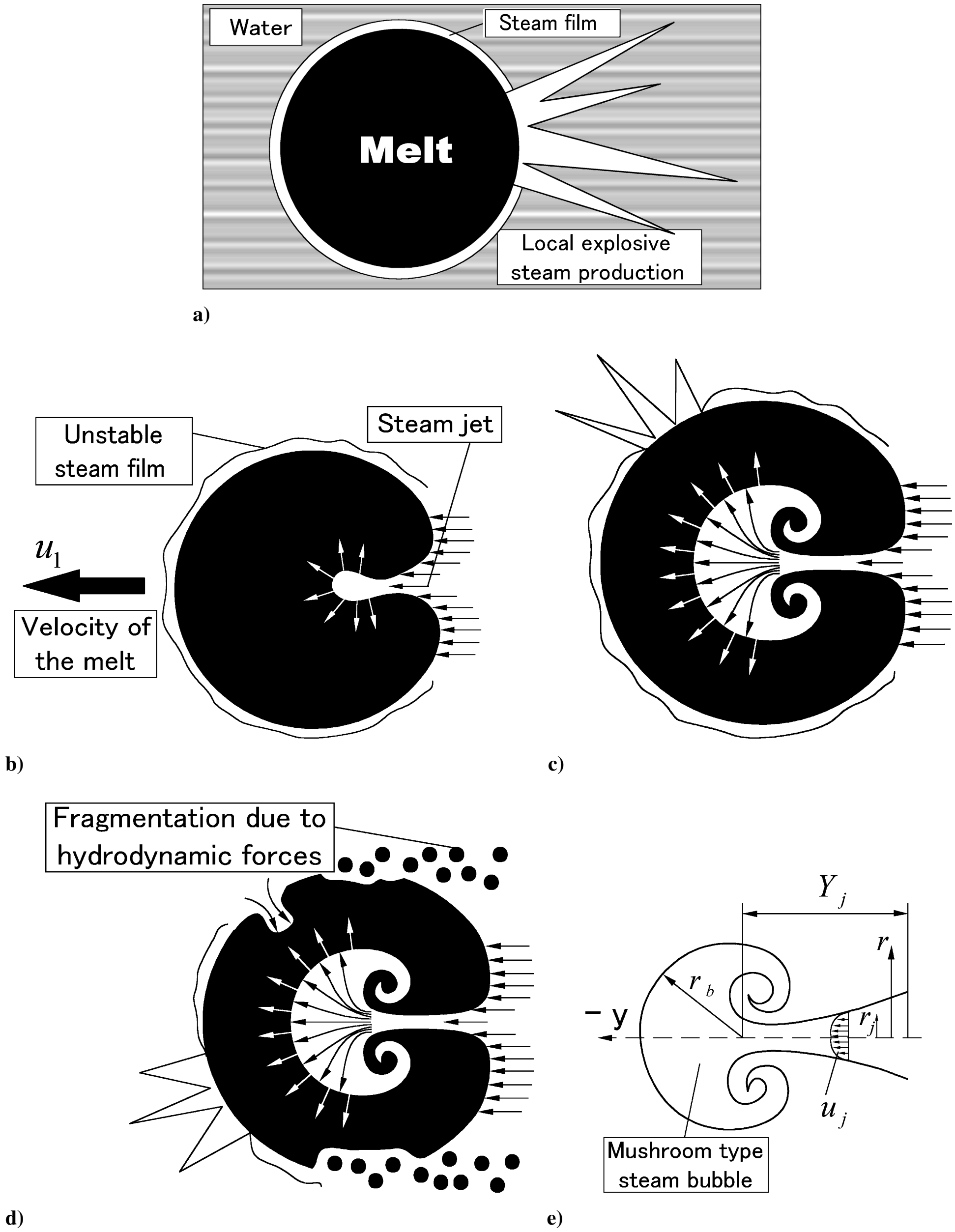

Fig. 4 Steam penetration into the melt.

Available experimental data about the heat transfer coefficient are rough and time-averaged values during the fragmentation process. According to a review of literature, the time-averaged value of the heat transfer coefficient is in the range of 10^5–10^6 $W \cdot m^{-2}K^{-1}$ when the heat transfer is to a high-density fluid.[14] However, there is a significant uncertainty concerning the accuracy of this range.[15,16] Especially, for the two-phase flow (the case of the steam explosion phenomenon), the heat transfer coefficient is very dependent on whether the fragments are in contact with the steam or water phase. When the fragments are in contact with the steam, the time-averaged value of the heat transfer coefficient is about 10^3 $W \cdot m^{-2}K^{-1}$. This value corresponds to the film-boiling regime if the melt temperature is about 3000 K. When the film collapses due to the decreasing melt temperature, the heat transfer coefficient becomes about 10^6 $W \cdot m^{-2}K^{-1}$ for the enhanced boiling regime.[15] Although the heat transfer area increases as a result of fine fragmentation, the heat transfer rate necessary for an explosive steam production per unit time is much greater than the steam production observed during the steady nucleate boiling regime.[17]

According to the heat transfer model developed by Fletcher and Thyagaraja,[18] the heat transfer coefficient between the melt and the coolant can be 10^7 $W \cdot m^{-2}K^{-1}$, even for the high void fractions such as 90%. They indicate that, if the heat transfer coefficient is 10^7 $W \cdot m^{-2}K^{-1}$, the propagation shock wave occurs for a spherical geometry. However, it does not occur for a spherical geometry if the heat transfer coefficient is reduced to 10^5 $W \cdot m^{-2}K^{-1}$. The heat transfer coefficient at the surface of UO_2 particles in contact with water is about 10^5 $W \cdot m^{-2}K^{-1}$. If the surface heat transfer coefficient exceeds about 10^7 $W \cdot m^{-2}K^{-1}$, it becomes diffusivity limited for UO_2 particles having 250 μm diameter.[19] An average heat transfer coefficient of 10^6 $W \cdot m^{-2}K^{-1}$ is obtained for a time interval of 100 μs in experiments with pulse-heated wires submerged in a water pool.[20]

Occurrence of the Shock Wave

As one of the necessary conditions for a large-scale steam explosion, triggering of only one melt particle must initiate a shock wave that causes the steam films around the other melt droplets to collapse while it propagates in the medium. Evaluation of the visual data of the ALPHA large-scale steam explosion experiments[8] revealed that the shock wave mainly propagates in the water. To initiate a shock wave, steam production as a result of triggering should be fast enough, such that the speed of the steam–water interface is greater than the speed of sound in the water. The initial speed of the steam–water interface is calculated as about 1810 m/s for a spherical melt droplet having a 0.5 cm radius by using the earlier calculated heat transfer coefficient. Initially, the water temperature is about 300 K for the ALPHA experiments. The speed of sound in water corresponding to this temperature is about 1450 m/s. Therefore, according to the suggested fragmentation model, steam production at the triggering stage is fast enough to create a shock wave.

Once the shock wave is produced, there will be no melt-water contact for that particular melt droplet. Melt-water contact rate (Fig. 4) is constrained by the physical parameters that ultimately result in the occurrence of shock wave. Model conservation equations are solved for the instant just before the fragmentation starts. Therefore, area enlargement due to the fine fragmentation is not taken into consideration. Of course, area enlargement will increase the speed of the steam–water interface by increasing the heat transfer rate.

Uncertainty Analysis

To understand how much uncertainty in the heat transfer coefficient is caused by assuming that r_b is accepted as $r_m/2$, the heat transfer coefficient h is calculated for several r_b values, that is, $r_m/2$, $r_m/3$, $r_m/4$, and $r_m/5$. The heat transfer coefficients h that correspond to those r_b values are 25.1×10^6, 27.1×10^6, 27.9×10^6, and 28.2×10^6 W $\cdot$ m^{-2}K^{-1}, respectively. In brief, a 25% increment in r_b (from $r_b = r_m/5$ to $r_b = r_m/4$) leads to a 1.4% decrease in h. A 32.8% increase in r_b (from $r_b = r_m/4$ to $r_b = r_m/3$) causes h to decrease 2.9%. If r_b is increased by 50.6% (from $r_b = r_m/3$ to $r_b = r_m/2$), h will decrease about 7%. Even for a large uncertainty range of r_b, such as a 150% increase (from $r_b = r_m/5$ to $r_b = r_m/2$), the heat transfer coefficient h will decrease only about 10.6%.

To understand the effect of melt radius on the heat transfer coefficient, h has been calculated for a variety of r_m values. Some examples are presented here: When the radius of melt is increased 50%, the necessary heat transfer coefficient leads to an explosion increases of about 50.2%. If the radius of the melt is doubled, the increase in the heat transfer coefficient will be 100.4%. Similarly, a 50% decrease in the melt radius corresponds to a 49.8% decrease in the heat transfer coefficient. These numerical results indicate that, when the radius of the melt increases, the necessary heat transfer rate should increase to obtain a small-scale steam explosion. For the smaller values of melt radius, comparatively smaller heat transfer rates can be sufficient to trigger the explosion. In other words, the degree of the melt breakup in the premixing stage is important in determining the percentage of the melt that contributes to the large-scale steam explosion. Indeed, comparatively finer melt breakup in the premixing stage, as in the case of melt and coolant injection modes, leads to more energetic steam explosions. This result is in good agreement with the widely accepted theory.

The effect of penetrating steam density on the heat transfer coefficient h is negligible, that is, a 50% decrease in the penetrating steam density can cause the heat transfer coefficient to decrease less than 0.001%.

It is obvious that the most influential parameter on the heat transfer coefficient is the triggering time. The heat transfer coefficient is almost inversely proportional to the triggering time, that is, a 100% increase in the triggering time can lead to a 50% decrease in the heat transfer coefficient for a certain geometry and experimental conditions. This result is quite reasonable. Because the amount of heat transfer necessary to obtain a small-scale steam explosion (triggering) is fixed during a certain triggering time, it is evident that the heat transfer coefficient should be inversely proportional to the triggering time. Some single-drop experiments, such as the one done at the Central Research Institute of Electric Power Industry, Japan, revealed that the triggering time is about 0.1 ms (Ref. 13). Therefore, 0.1 ms was used as the triggering time in the calculation of h.

Conclusions

An alternative fragmentation theory has been introduced for the triggering stage of the steam explosion phenomena. The theory consists of two parts, hydrodynamic and thermal fragmentations, which are simultaneous and interacting with each other. For the hydrodynamic part, a qualitative idea explaining the physical mechanism of the fragmentation of a single melt droplet has been suggested. Hydrodynamic forces applied on the vibrating melt droplet by the surrounding water cause the melt droplet to be deformed. Employing the empirical relationship between the Ohnesorge number and the critical Weber number, the necessary minimum velocity to initiate the fragmentation is found to be 0.775 m/s under the same experimental conditions of an actual large-scale steam explosion experiment. This result is used in the second part of the suggested fragmentation theory to solve the conservation equations.

Steam penetration into the melt and continuously expanding steam bubble leading to the burst and disintegration of the melt droplet constitute the thermal part of the suggested theory. When the model equations are solved, the heat transfer coefficient is calculated as about $h_{\text{total}} = 25 \times 10^6$W $\cdot$ m^{-2}K^{-1}. In conclusion, it has been demonstrated that the steam production based on the calculated heat transfer coefficient is fast enough to initiate a shock wave, which is one of the necessary conditions to have a large-scale steam explosion. To determine the reliability of the suggested fragmentation theory, an uncertainty analysis has also been performed.

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