

Thermodynamic Analysis of Vapor Explosion Phenomena

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증기폭발 현상의 열역학적 해석

방광현

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Abstract

A vapor explosion has been a concern in nuclear reactor safety due to its potential for a destructive mechanical energy release. In order to properly assess the hazard of a vapor explosion, it is necessary to accurately estimate the conversion efficiency of the thermal energy to mechanical energy. In the absence of a complete model to determine the explosive energy yield, one may have to rely on a simpler upper bound estimate such as a thermodynamic model. This paper discusses various thermodynamic models and presents a clarification of each model in their mathematical formulation and the thermodynamic work conversion. It is shown that the work release in the shock adiabatic model of Board and Hall is essentially equal to that of Hicks-Menzies thermodynamic model. The effect of coolant void fraction on the explosion efficiency is also predicted based on these thermodynamic models. Finally, the Hicks-Menzies model is modified to account for the chemical reaction between a metallic fuel and water and the resultant effects on the explosion expansion work are discussed.

요 약

증기폭발이 발생하면 파괴적인 동력에너지가 방출될 가능성이 있으므로, 이 현상은 원자력 발전소 안전성 연구 분야에서 중요한 현상으로 지목되어 왔다. 따라서 증기폭발이 미치는 영향을 분석하기 위해서는 폭발시 수반되는 열에너지가 동력에너지로 전환되는 비율을 정확히 해석할 수 있어야 한다. 그러나, 정확한 해석 방법의 개발이 이루어지지 않은 현 상황에서는 순수히 이론에 근거한 열역학적 해석 방법 등을 이용할 수 있으며, 이러한 접근 방식은 그 결과가 보수적이라는데 그 의미가 있다. 본 논문에서는 현재까지 알려진 열역학적 해석 방법들을 정리하였고, 이론적으로 모순된 부분을 수정하여 비교하였다. 지금까지 알려진 바와는 달리, Hicks-Menzies 모델과 Board-Hall 모델은 에너지 전환율에서 동일한 결과를 나타냄을 보였다. 또한 증기폭발에서 냉각수 초기 기공율의 영향을 계산, 검토하였으며, 금속의 발열반응의 영향을 분석할 수 있는 열역학적 모델을 제시하였다.

1. Introduction

In present day nuclear fission reactors, if complete and prolonged failure of normal and emergency coolant flow occurs, fission product decay heat could cause melting of the reactor fuel. If the molten fuel mass accumulates it may eventually be brought into contact with residual water either in-vessel or ex-vessel. The contact of the molten fuel with the coolant, so called Fuel-Coolant Interaction (FCI), may have a number of consequences depending upon the heat transfer rate between the molten fuel and water. One of the possible consequences of the FCI is an energetic explosion, often called, a vapor explosion. The occurrence of such an energetic FCI in the course of a postulated core meltdown accident is a concern in nuclear reactor safety since it could challenge the containment integrity and contribute to the release of radioisotopes into the environment.

On the basis of experimental observations[1], an energetic FCI may have the four distinct phases of (1) premixing, (2) triggering, (3) explosion propagation, and (4) expansion. The expansion phase often involves fluid-structure interactions and may cause damage to surrounding structures. A complete mechanistic model to estimate the potential hazard of an energetic FCI has not been available to safety analysts due to the present lack of understanding of detailed mixing and fragmentation mechanisms. Although a reliable mechanistic model is desirable for an accurate assessment of an FCI event, a thermodynamic model is often used in reactor safety studies and, in particular, design of laboratory experiments or other research facilities since it is relatively straightforward to formulate and it generally provides an estimate of the upper bound explosion work potential.

A thermodynamic model generally describes the mixing and explosion expansion which connect

the three points of (1) the initial coarse mixture, (2) the equilibrium high-pressure state, and (3) the final expanded state (see Figure 1). Since the work done during the expansion is a path-dependent quantity, the path of constant entropy of the fuel-coolant mixture can provide the maximum work output as was proposed by Hicks and Menzies[2]. However, this model has been considered as too conservative because the high explosion pressure and the mechanical work output predicted by this model are not realized in experiments. Subsequent to the Hicks-Menzies model, an alternative isobaric expansion path was proposed for more realistic explosion pressure. However, since this model requires experimental measurements, it suffers from predictive capability. Recently, Hall[3] proposed a model similar to the isobaric expansion, where the work output is based on the reversible compression of the surrounding fluids. Board and Hall[4] proposed another thermodynamic treatment of the energetic vapor explosions termed the shock adiabatic model. This model was developed by applying the analogy between the vapor explosion and chemical detonation and sought to consider the explosion character under steady propagation conditions.

The purpose of this paper is to review the available thermodynamic models of fuel-coolant interactions and to present a better clarification of their mathematical formulation and the relationship of their thermodynamic work conversion. For this purpose, the Hicks-Menzies, Hall, and shock adiabatic models are chosen because these models are purely theoretically based. Also, new formulations of these models using a complete equation of state for the coolant are demonstrated. The effect of coolant void fraction and the presence of chemical reactions between the fuel and coolant in the thermodynamic analysis are also briefly discussed.

2. Thermodynamic Models of Fuel–Coolant Interactions

2.1. Hicks–Menzies Model

The Hicks–Menzies thermodynamic model consists of two adiabatic processes: (1) constant-volume mixing of the fuel and coolant to equilibrium temperature and pressure and (2) constant-entropy expansion of the mixture (or coolant) to the end state. The thermodynamic state of the equilibrium mixture is related to the initial states of the fuel and coolant by the conservation of internal energy (no work due to constant-volume mixing).

$$m_h u_{h,2} + m_c u_{c,2} = m_h u_{h,1} + m_c u_{c,1} \quad (1)$$

The mixture expands along the isentropic path to the end state and the work done during this expansion process is the difference in the internal energy between the two states.

$$W_{HM} = m_h(u_{h,2} - u_{h,3}) + m_c(u_{c,2} - u_{c,3}) \quad (2)$$

The end state in this model is either given as a specified pressure or determined by the pressure equilibrium of the mixture and the surrounding fluid in the case of an FCI occurring in a fixed volume. In this latter case, the response of the surrounding fluid is treated as an adiabatic and irreversible process.

The mixture expansion can be either with the fuel and coolant in thermal equilibrium (isentropic mixture expansion) or with the coolant expanding adiabatically (isentropic coolant expansion). The latter expansion path provides a model for the case where the coolant vapor, produced during the expansion, halts further heat transfer from the fuel to coolant due to sufficient vapor blanketing.

This model has been further refined by removing the assumptions in the original work such as constant thermodynamic properties of fuel and coolant. Most recently, Cline et al. [5] developed

a generalized form of the Hicks–Menzies model by applying the complete equations of state for the fuel and coolant. However, their results showed an inconsistency such that the work in the vapor blanket mode (isentropic coolant expansion) is unphysically greater than the non-blanketed case (isentropic mixture expansion) in certain range of the liquid coolant to fuel volume ratio. Because heat transfer is halted in the vapor blanket mode, the work in this case should be smaller than that in the isentropic mixture expansion. This apparent error in their model can not be explained.

It has been widely recognized that the Hicks–Menzies thermodynamic model predicts a theoretical maximum work potential in fuel–coolant interactions. The mechanical energy release in the past FCI experiments were often compared with this work potential as a measure of their relative efficiency. However, neither the high equilibrium pressure nor the high conversion ratio of thermal energy to mechanical work predicted by this model has been realized in experiments.

2.2. Hall Model

While the Hicks–Menzies type models provide an estimate of the maximum thermodynamic work, Hall [3] proposed a model which he claimed predicts a lower limit. In this model, the compression of the fluid around the interaction zone in a fixed volume occurs reversibly and adiabatically, and the expansion of the fuel–coolant mixture is irreversible.

This model consists of two adiabatic processes for the fuel–coolant mixture: (1) constant-volume mixing of fuel and coolant to the end state pressure, and (2) constant-pressure expansion until the pressure is uniform throughout the system (see Figure 1). The end state temperatures of the fuel and coolant are assumed to be uniform. The surrounding fluid is compressed to the end state pressure in an adiabatic and reversible manner.

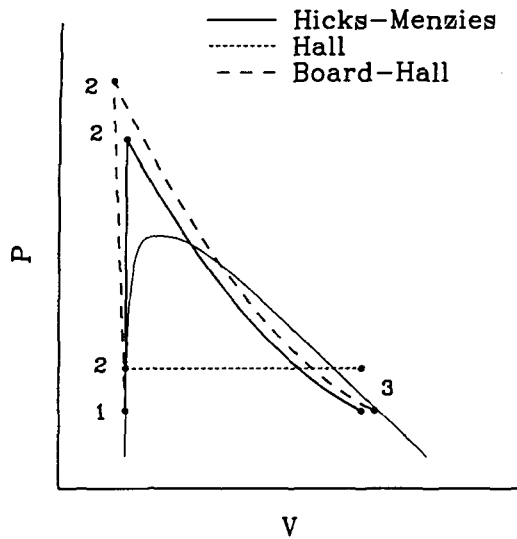


Fig. 1. Thermodynamic Path of a Vapor Explosion on the P - v Diagram of Coolant

The minimum work required for this isentropic compression of the surrounding fluid, if the compression work of any liquid is negligible and the gas is an ideal gas, is

$$W_{sur} = \frac{P_1 V_{sur,1}}{\gamma-1} \left\{ \left(\frac{P_3}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \quad (3)$$

This work is claimed to be a lower limit of the FCI work that could be done if the compression were irreversible. Hall proposed this work as the work output in his model.

The end state in this model is determined by the pressure equilibrium of the mixture and surrounding fluid at the end state. For the fuel-coolant mixture in an adiabatic system, the energy balance is

$$W_m + \Delta U = 0 \quad (4)$$

$$\Delta U = (m_h u_{h,3} + m_c u_{c,3}) - (m_h u_{h,1} + m_c u_{c,1}) \quad (5)$$

It is noted that these two equations are written in different forms in the Hall's original paper [3] (Eq. (2) and Eq. (3)) which is unexplainable. Since the isobaric expansion of the mixture is assumed in Hall's model,

$$W_m = P_3 (V_{m,3} - V_{m,1}) \quad (6)$$

This, W_m , is the work done during the irreversible expansion of the mixture at constant pressure (end state pressure). However, one must note that this work is thermodynamic path-dependent and can be larger or smaller depending on the path chosen. If the mixture pressure is equilibrated with the surrounding ambient pressure throughout the process, the work in this case is definitely the minimum work that could be done by the mixture; i.e., $W_m = W_{sur}$ in Eq. (6) where W_{sur} is given by Eq. (3).

This model represents the simplest quasistatic process that can link the initial and end states of the system. However, it should be noted that the end state pressure can generally be different depending on the path chosen and this model is only applicable to a fixed volume system because it considers the minimum work in terms of the surrounding fluids.

2.3. Board-Hall Shock Adiabatic Model

A theoretical prediction of the explosion pressure and propagation velocity without a detailed knowledge of fuel-coolant mixing and energy transfer rate can be obtained by applying the steady-state shock adiabatic model which was originally proposed by Board and Hall [4]. This model was developed by applying the classical theory of detonation in chemically reactive flows to the one dimensional case of an explosion front propagating through a coarsely mixed region of fuel and coolant.

Consider a planar explosion front which is steadily progressing through uniformly mixed materials initially at rest, and leaving behind it an equilibrium mixture of 'exploded' materials. By applying the equations of conservation of mass, momentum and energy, the Hugoniot relationship can be derived which defines a unique relationship between the possible values of P_2 and v_2 :

$$\frac{1}{2}(P_1 + P_2)(v_1 - v_2) = u_2 - u_1 \quad (7)$$

The velocities U_1 and U_2 in the moving frame of reference of shock front are given by

$$U_1 = v_1 \sqrt{\frac{P_2 - P_1}{v_1 - v_2}} \quad (8)$$

$$U_2 = v_2 \sqrt{\frac{P_2 - P_1}{v_1 - v_2}} \quad (9)$$

Here, U_1 corresponds to the shock propagation velocity and the velocity of the material behind the shock front in the laboratory frame is $U_1 - U_2$. Therefore, the medium behind the shock front moves in the direction of the front. Accordingly, the region behind the front must be followed by a region of expansion, which may be thought of as providing the driving power for the explosion. The leading edge of this expansion region is a rarefaction wave which travels at the local mixture sound speed, c_2 ; for this to be stationary in the frame of shock front we must have $U_2 = c_2$ (Chapman–Jouguet condition). This condition defines a unique equilibrium state on the detonation branch of the Hugoniot curve (Eq. (7)). Also, the detonation condition ($P_2 > P_1$) implies that the medium behind the shock front must be compressed ($v_2 < v_1$), as shown in Figure 1.

Now, the work in the isentropic expansion of the mixture at the C–J condition to a specified end state can be calculated in a similar manner to Hicks–Menzie's model, but one must include the kinetic energy at the C–J state.

$$W_{2-3} = m_h(u_{h,2} - u_{h,3}) + m_c(u_{c,2} - u_{c,3}) + (m_h + m_c) \frac{(U_1 - U_2)^2}{2} \quad (10)$$

It is noted that since the Chapman–Jouguet state has the least specific entropy of any along the shock adiabat including the Hicks–Menzie's point (isochoric path), W_{2-3} in Eq. (10) is always greater than W_{HM} in Eq. (2). This was the result

originally pointed out in the Board–Hall's study [4]. However, the traveling shock wave in this model is self-sustaining; i.e., the driving power for the explosion is provided by the expansion of the mixture. Thus, one should take account of the initial compression work done by the shock wave in calculating the actual net work potential. The work done by a shock wave to a medium initially at rest is the sum of internal and kinetic energy increases. This work is [6]

$$W_{com} = (m_h + m_c)P_2(v_1 - v_2) \quad (11)$$

Therefore, the net thermodynamic work output in the Board–Hall's detonation model and subsequent isentropic expansion is

$$W_{BH} = W_{2-3} - W_{com} \quad (12)$$

and must be accounted for in any comparison to other models or experimental data. This has not been previously done in past analyses.

3. Comparison and Discussion

In order to demonstrate and compare the predictions of the thermodynamic work output by a vapor explosion with these three thermodynamic models, a series of calculations have been carried out. Specifically, comparisons are discussed for the Hicks–Menzie's and Hall models and for the Hicks–Menzie's and shock adiabatic models.

Figure 2 illustrates the conversion ratios at various volume ratios of liquid coolant to fuel calculated by the Hicks–Menzie's and Hall models for thermite as the fuel and water as the coolant for a fixed volume system. Thermite is a fuel simulant used in experiments consisting of a mixture of iron and alumina (Fe–55 w/o and Al_2O_3 –45 w/o). In these calculations, the fuel and coolant temperatures are 3100 K and 323 K, respectively, and a 10% coolant vapor volume fraction is assumed at the initial state. The total system volume is 25

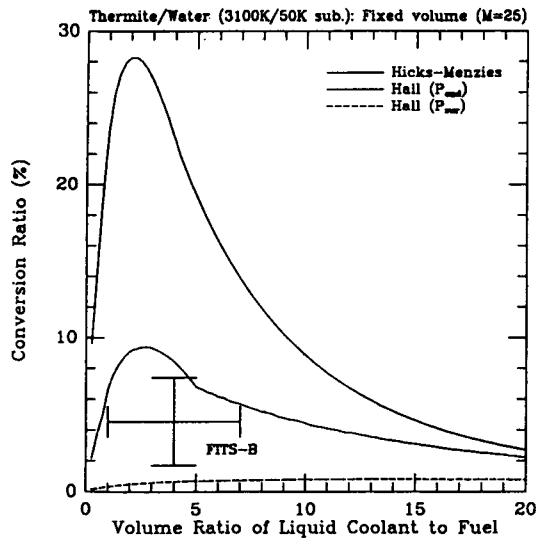


Fig. 2. Comparisons of FCI Work Potential Predicted by Hicks-Menzies and Hall Models in a Fixed Volume System

times the volume of the fuel-coolant mixture at its initial state. This volume is a reasonable representation of the FITS-B series experimental conditions[7] and was chosen in these calculations for the comparison purpose with the experimental data. The density and specific heat of the fuel are assumed to be constant. This is a reasonable assumption because the fuel material is almost incompressible compared with the liquid-vapor mixture of the coolant and the internal energy of the elements for the fuel materials are fairly linear with temperature (JANAF table[8]). The thermodynamic properties of water are provided by the program package of the NBS/NRC Steam Tables [9]. The surrounding fluid is air with the molar mass of 29 and the specific heat ratio of 1.4.

The results show that the thermodynamic maximum conversion of thermal energy to mechanical work is obtained at the volume ratio of liquid coolant to fuel of about two in both models. This is an agreement with past discussions of maximum Hicks-Menzies work at equal volumes[2]. It is also interesting to note that the predictions by the

Hall model do not appear to be the lower limit of explosion work output when compared with the FITS-B experimental data. In this figure, the FITS-B experimental data are presented as a range of values with uncertainties since the actual reacted masses of the fuel and coolant are not precisely known and the calculated conversion ratios using the measured variables are different depending on the method used[10].

The curve with the lowest conversion ratio shown in this figure is obtained by using the Hall model, but the pressure of the fuel-coolant mixture is equilibrated with the surrounding fluid throughout the process (mechanical equilibrium in the system) and $W_m = W_{sur}$ instead of using Eq. (6). This work is the minimum work that the mixture could do as discussed in the previous section. However, such a fuel-coolant mixture pressure trace was not measured in the FCI experiments, and this identifies a true lower bound for an adiabatic expansion.

Considering the Board-Hall model, our new interpretation of the vapor explosion work in the isentropic expansion of the Chapman-Jouguet state raises the question of the relationship between W_{HM} and W_{BH} . In order to illustrate this relationship, a series of calculation have been carried out for corium and water interactions. Corium is a term used for a mixture of molten core materials (e.g., UO_2/ZrO_2 -85 w/o and $Zr/Steel$ -15 w/o). In these calculations, the assumptions of constant density and specific heat are again applied to the fuel properties. In the Board-Hall model, the sonic speed of the mixture to determine the C-J state was computed using the following formula based on the homogeneous flow model for the fuel, liquid coolant and vapor coolant:

$$c_m = \left[\rho_m^2 \frac{x_h}{\rho_h^2 c_h^2} + \frac{x_f}{\rho_f^2 c_f^2} + \frac{x_g}{\rho_g^2 c_g^2} \right]^{-\frac{1}{2}} \quad (13)$$

It is recognized that there are other suggested

criteria for the C-J state [12]. Basic Hugoniot theory does not indicate which criteria is most appropriate. However, this criteria is most consistent with the Board-Hall conceptual model.

The results for corium (3000 K) and water (358 K) with varying initial coolant void fraction are shown in Figure 3 for a condition of equal volumes of liquid coolant and fuel. The net work output in the Board-Hall's detonation model ($W_{2-3}-W_{com}$) is compared with the work predicted by the Hicks-Menzies model. It is shown that based on the new interpretation of the net work output the two models can predict similar amount of work output although these are not identical. A small difference can be caused by the iterative solution procedure, however, this is a small effect ($\ll 1\%$). One should not expect that these would be the same since the thermodynamic work output is determined by the specified expansion path and in each case (isentropic mixture or coolant expansion) the initial and final thermodynamic states are different. A similar qualitative behavior between W_{HM} and W_{BH} was also found in the

results for thermite/water, aluminum/water, and tin/water.

4. Effect of Initial Coolant Void Fraction

When a molten fuel material is poured into a pool of coolant, the fuel breaks up and forms a coarse mixture with the coolant liquid and vapor. The heat transfer rate between the fuel and the coolant is relatively low (i.e., film boiling) and the volume fractions of the three fluid components of the mixture are governed by the liquid breakup mechanisms, multi-fluid hydrodynamics and heat transfer. The uncertainty associated with the material distribution in the mixing stage often leaves the component volume fractions of the mixture as arbitrary parameters in the subsequent analysis of explosion propagation and expansion.

Figure 4 shows the change of the thermodynamic conversion ratio due to different initial coolant void fractions at various volume ratio of the liquid coolant to fuel. These calculations were carried out for Iron-Alumina thermite (3100 K) and water

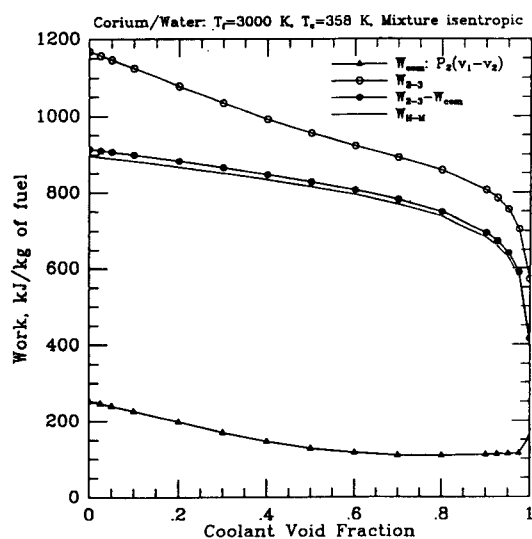


Fig. 3. Comparisons of FCI Work Potential Predicted by Hicks-Menzies and Board-Hall models: Isentropic Mixture Expansion

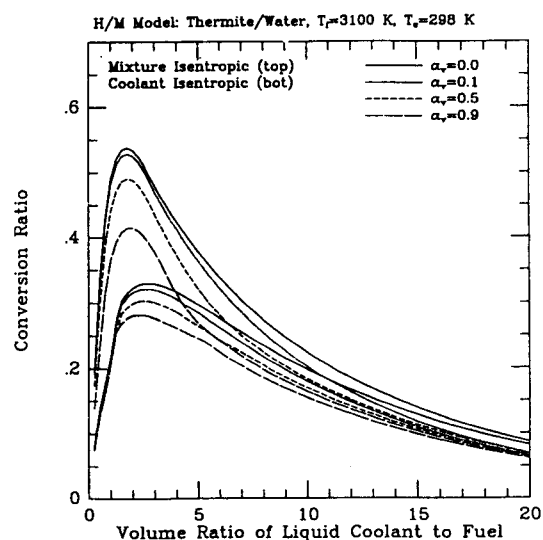


Fig. 4. Effect of Initial Coolant Void Fraction Predicted by Hicks-Menzies Model

(298 K) using the Hicks–Menzies thermodynamic model. It is shown that the void fraction of 90% reduces the conversion ratio by 15 to 20 percent from the case of no void. One should note that the thermodynamic maximum of the work output is obtained given an infinitely constrained system in which the energy transfer between the fuel and coolant is completed with no volume change. In this case, the void fraction is not a significant parameter since the mass and heat capacity of the vapor are small and the rate of the heat transport process is not involved. The presence of the vapor void reduces the work output because the mixture has already expanded prior to the explosion expansion to accommodate the vapor volume and thus reduces the equilibrium explosion pressure. Accordingly, the effect of initial coolant void fraction on the thermodynamic work output is small. It is noted, however, that the presence of large vapor void may reduce the conversion of the thermal energy to mechanical work significantly in real FCIs since the vapor blanket is the major resistance in the heat transfer from the fuel to coolant liquid.

The currently available advanced models for explosion propagation with time-dependent kinetic processes and hydrodynamic solution often show the occurrence of self-sustaining explosion propagations in a high-void system[11]. However, in a high-void system the vapor tends to be the continuous medium (i.e., dispersed flow regime) so that the direct contact of fragmented fuel particles and coolant liquid is not likely to occur, which would be the key to the rapid heat transfer and explosive vaporization in an actual explosion. Although it appears that the modeling of fuel-coolant interactions must accompany simultaneous development of constitutive models such as fuel fragmentation mechanism and heat transfer rate in various flow regimes, such integrated models must be validated with benchmark experimental data, particularly on the effect of initial

void fraction, which is not currently available.

5. Thermodynamic Modeling with Chemical Reaction

When the molten core materials contain metallic components, these metals can oxidize in the presence of water, atmosphere or concrete and produce hydrogen. The hydrogen generation in the course of severe reactor accidents is of concern primarily for its possible subsequent combustion and the resulting high pressure and temperature spike in the containment atmosphere. However, the presence of metallic components in the fuel in fuel-coolant interactions may contribute to more energetic vapor explosions since the metal reacts with water exothermically, possibly on a time scale of the explosion. This chemical reaction heat is then added to the available energy of the fuel-coolant mixture and the reaction rate increases rapidly as the fuel fragments.

In order to investigate the effect of chemical reactions in fuel-coolant interactions, the Hick-

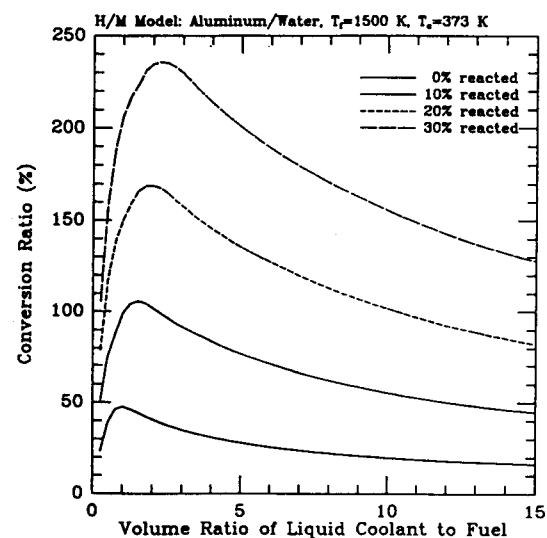


Fig. 5. Effect of Chemical Reaction Predicted by Hicks–Menzies Model

s-Menzies model was modified to account for the reaction heat. Although the metal oxidation is a kinetic process, it is assumed that all the reaction heat of the metal oxidized is added to the internal energy of the fuel-coolant mixture at the high-pressure equilibrium state. Accordingly, the Eq.

(1) is modified as

$$m_h u_{h,2} + m_c u_{c,2} = m_h u_{h,1} + m_c u_{c,1} + f m_h \dot{Q}, \quad (14)$$

The fraction of the metal oxidized, f , is varied parametrically in this model.

To demonstrate the effect of the presence of chemical reactions on the thermodynamic work output, a series of calculations have been carried out for aluminum and water interactions. The chemical reaction heat in this case is 15.11 MJ per kilogram of aluminum reacted and the initial temperatures of the fuel and coolant are 1500 K and 373 K, respectively. Both the initial and end state pressures are 0.1 MPa.

Figure 5 shows the effect of the chemical reaction on the conversion ratio with various fractions of metal oxidized. The conversion ratio in this figure is based on the thermal energy of the fuel and represents the case of isentropic mixture expansion. It is noted that each ten percent increase in the amount of the metal oxidized doubles the conversion ratio from the case of no metal oxidation. The maximum conversion ratio is seen at about equal volumes of liquid coolant and fuel in case of no metal oxidation, and this occurs at higher volume ratio as the fraction of metal oxidized increases. This trend is also seen when the initial fuel temperature is increased. Since, in this model, the chemical reaction heat is added to the internal energy of the fuel-coolant mixture at the high pressure equilibrium state, the increase in the initial fuel temperature or the increase in the fraction of metal oxidized results in the same trend on the volume ratio of maximum conversion ratio. If experiments become available in which the explo-

sion energetics from a metal-water interaction is investigated, such a model could be useful to produce a bounding analysis.

6. Conclusions

Three thermodynamic models of energetic fuel-coolant interactions, Hicks-Menzies, Hall, and shock adiabatic models, are reviewed and a clarification of their mathematical formulations and the thermodynamic work conversion are presented. The solution of each model using the exact equation of state of water is also demonstrated for some sample cases. The Hicks-Menzies model is modified to account for chemical reaction between a metallic fuel and water and the effect on the conversion ratio is discussed.

The Hicks-Menzies model predicts the thermodynamic maximum work, but its conservative estimation of explosion pressure and conversion ratio may limit its usefulness. The Hall model predicts more realistic work conversion than the Hicks-Menzies. However, in Hall's model, the choice of the isobaric expansion of the mixture at the end state pressure bears no theoretical basis and it is rather an arbitrary choice among the many possible irreversible processes. A true qualified lower limit of the FCI work is introduced as the work done under the mechanical equilibrium in the system with the given assumptions ($W_m = W_{sur}$ in Eq. (4)). A new interpretation of the thermodynamic work in the Board-Hall's shock adiabatic model is presented and the results are compared with the results of Hicks-Menzies model. It is shown that Hicks-Menzies model and shock adiabatic model can predict similar amount of work output in vapor explosions when the work done during the isentropic expansion from the C-J state is reduced by the compression work done by a shock wave.

Although such thermodynamic models can provide a theoretical maximum work potential in an energetic FCI event, these models are useful tools

for a conservative assessment of its potential hazard, and in particular, for the design of energetic FCI experiments. In addition, the shock adiabatic model can provide the dynamic explosion pressure as well as the conservative work potential.

In the thermodynamic analysis of energetic FCIs, the high initial coolant void fraction does not seem to lower the work potential significantly, which is not likely to be true in a real FCI event. This trend is also often found in the results of the currently available advanced computer models. This suggests that the future research on the fuel-coolant interactions must be directed to not only developing the detailed mechanistic models which are currently lacking, but also providing benchmark experimental data for model validation under these fuel-coolant mixture conditions.

Acknowledgment

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Nomenclature

c	speed of sound
m	mass
P	pressure
\dot{Q}_r	chemical reaction heat
u	specific internal energy
U	velocity
v, V	volume
W	work
x	mass fraction
ρ	density
γ	specific heat ratio of gas

Subscript

I	initial state
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2	high-pressure equilibrium state
3	final state
c	coolant
f	coolant liquid
g	coolant vapor
h	fuel
m	mixture
sur	surrounding fluid

References

1. M.L. CORRADINI, B.J. KIM, and M.D. OH, "Vapor Explosions in Light Water Reactors : A Review of Theory and Modeling," Prog. Nucl. Energy, Vol. 22, pp. 1-117, 1988.
2. E.P. HICKS and D.C. MENZIES, "Theoretical Studies on the Fast Reactor Maximum Accidents," Argonne National Laboratory Report ANL-7120, pp. 654-670, 1965.
3. A.N. HALL, "Outline of a New Thermodynamic Model of Energetic Fuel-Coolant Interactions," Nucl. Eng. Design, Vol. 109, pp. 407-415, 1988.
4. S.J. BOARD and R.W. HALL, "Propagation of Thermal Explosions Part 2 : A Theoretical Model," Central Electricity Generating Board Report RD/B/N3249, 1974.
5. D.D. CLINE, L.T. PONG, D.F. BECK, and M. BERMAN, "An Equation of State Formulation for Hicks-Menzies FCI Efficiencies," Nat. Heat Trans. Conf., AIChE Sym. Series No. 269, Vol. 85, pp. 48-53, 1989.
6. Y.B. ZEL'DOVICH and Y.P. RAIZER, Elements of Gasdynamics and the Classical Theory of Shock Waves, Academic Press, 1968.
7. D.E. MITCHELL and N.A. EVANS, "Steam Explosion Experiments at Intermediate Scale : FITSB Series," SAND83-1057, Sandia National Laboratories, 1986.
8. JANAF Thermochemical Tables, NSRDS-

- NBS-37, 1971.
9. L. HAAR, J.S. GALLAGHER, and G.S. KELL, NBS/NRC Steam Tables: Thermodynamic and Transport Properties and Computer Programs for Vapor and Liquid States of Water in SI Units, Hemisphere Pub., 1984.
 10. Y.M. FARAWILA and S.I. ABDEL-KHALIK, "On the Calculation of Steam Explosion Conversion Ratios from Experimental Data," Nucl. Sci. Engr., Vol. 104, pp. 288-295, 1990.
 11. D.F. FLETCHER and A. THYAGARAJA, "A Mathematical Model of Melt/Water Detonations," Appl. Math. Model., Vol. 13, pp. 339-347, 1989.
 12. D.L. FROST, J.H.S. LEE, G. CICCARELLI, "The Use of Hugoniot Analysis for the Propagation of Vapor Explosion Waves," Shock Waves, Vol. 1, pp. 99-110, 1991.