Quantitative Analysis of Explosion of an RDF silo

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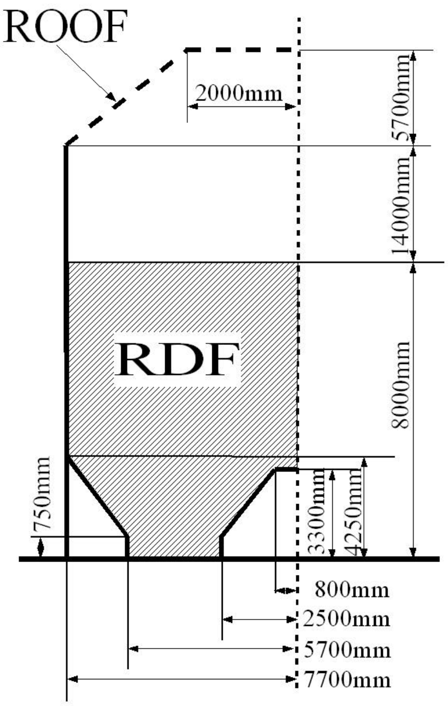
Introduction

Municipal solid waste is used as an energy source to reduce carbon dioxide emission in large cities. RDF(Refused Delivered Fuel) is produced from municipal solid waste in five model areas of medium cities in Japan. The produced RDF was planned to store during the maintenance period of the RDF power plan. The maximum length of the storage was planned five month.
An RDF silo of 15 m diameter overheated within one month after the loading in winter of 2002. The RDF silo was unloaded and a series of modification was carried out for six months. The RDF silo was reloaded in summer of 2003. The RDF silo overheated again within one month after the reloading. The operator of the RDF power plant tried to cool the RDF silo by injecting water to the overheated area. A small explosion blew four workers from the silo during the cooling effort. The operator of the RDF power plant asked the local fire department to cooperate the cooling effort of the silo. During the cooling effort, an explosion killed two fire fighters on the roof of the silo and blew the roof 190 m from the silo. The used RDF was tested with small scale experimental apparatus before the real scale operation. The explosion risk of the used RDF was considered as low as practically not hazardous based on the small scale experiment.
After the killing of two fire fighters, National Research Institute of Fire and Disaster investigated the fire and explosion of the RDF silo. The heat accumulation of the RDF pile was studied with small scale and medium scale experiments. The quantitative analysis of the formation of explosive mixture in the RDF silo was carried out with small scale experiments. In this study, a quantitative analysis of the explosion has been carried out to understand the energy source which blew the roof of the RDF silo of 10 ton.

Silo Structure

A cross sectional area of the RDF silo is shown in figure 1. The height of the silo is 27.7 m from the basement. The diameter is 15.4 m at the basement. Feeding mechanisms located at the bottom section. RDF was suppled from the opening at the roof. Due to the openings to the external equipments, the silo is not airtight. The height of the RDF pile is 8 m at the catastrophic explosion. The roof section was lost at the explosion. The basement of the silo was also damaged by the explosion.
An aerial view of thermal image of the RDF silo after the explosion is shown in figure 2. A large hot area is seen on the surface of the RDF pile in the damaged silo. The temperature of the peripheral area is lower than that of the central area due to the heat loss from the external wall of the silo. The RDF pile continued heating until the removal of the pile. The overheating of the RDF pile was prevented by applying water at large discharge rate.
RDF decomposes exothermically at elevated temperature in air.



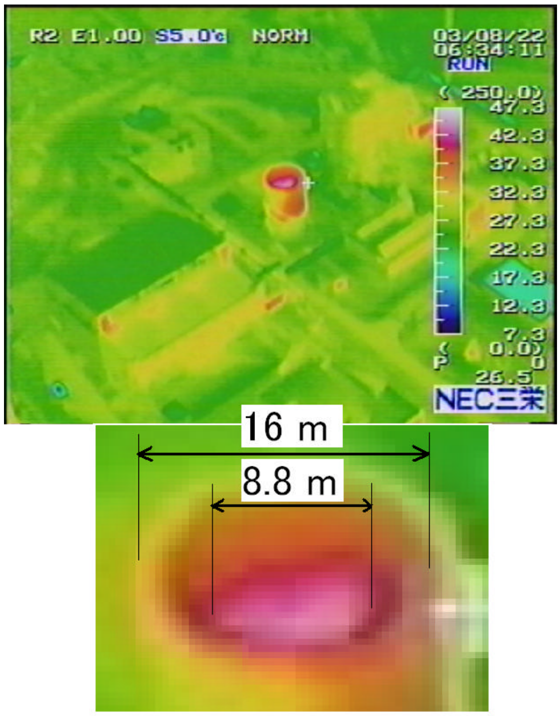


Fig.1 Cross section of RDF silo

Fig. 2 Aerial view of RDF silo

Quantitative Analysis of Explosion

Accumulated Energy of Gas

The void volume of the RDF silo, V was 3.07×10^3 m^3. The overpressure at the breaking roof, P was estimated about 60 k Pa by KHK(Kikenbutsu Hoangijyustu Kyoukai). Presuming that the leakage of the gas from the RDF silo is small and the gas in the silo is ideal gas, the mean temperature of the gas in the silo, T is estimated with the initial temperature, 300 K.

$$T = 300 * (101 \times 10^3 + 60 \times 10^3) / (101 \times 10^3) = 478 \text{ [K]} \quad (1)$$

The increase of the internal energy of the gas in the silo, E_1 is estimated with the mean temperature of the gas and the heat capacity at constant volume of air, c_v.

$$E_1 = 3.07 \times 10^3 / (22.4 \times 10^{-3}) \times 21 \times (478 - 300) = 5.12 \times 10^8 \text{ [J]} \quad (2)$$

Volume of Air to Generate Accumulated Energy

Presuming that the increase of the energy was caused by exothermic reaction with oxygen in the air, the volume of the air used by the exothermic reaction, V_1 is estimated by means of oxygen consumption method.

$V_1 = E_1 / (3.03 \times 10^{3}) / 29.0 * 22.4 \times 10^{-3} = 131\ [m^3]$ (3)

The volume of the air, V_1 is 4.27 % of the void volume of the RDF silo, V. The weight of the air of volume V_1 is

$M_1 = E_1 / (3.03 \times 10^3) / (1 \times 10^3) = 169\ [kg]$ (4)

The thickness of the air layer, d is determined by dividing the air volume with the surface area of the RDF pile, 186 m^2.

$d = V_1 / 186 = 0.704\ [m]$ (5)

The Rayleigh number based on the thickness of the air layer, Ra_d is

$Ra_d = g\ \ ß\ \ dT\ \ d^3 / a / n = 9.8 (1/273) dT\ d^3 / (2.08 \times 10^{-5}) / (1.50 \times 10^{-5})$

$= 4.01 \times 10^7\ dT$ (6)

Where dT is the temperature difference between the upper and lower part of the air layer. If the lower part of the air layer is heated by the surface of the RDF pile and dT exceeds 2.5×10^{-5} K , the Rayleigh number exceeds a critical value of cellular convection, 1108. If the surface of the RDF pile is cooled with water which temperature is lower than the ambient temperature, a stratified motionless layer of mixture forms on the surface of the RDF pile.

Weight of RDF to generate Accumulated Energy

The weight of RDF used by the exothermic reaction, M_2 is estimated with the heat of combustion of RDF, 2.1×10^7 J/kg.

$M_2 = E_1 / 2.1 \times 10^{7} = 24.4\ [kg]$ (7)

The weight of the RDF used by the exothermic reaction is 0.004 % of the stored RDF of 600 ton at the explosion.

Kinematic Energy of the Silo Roof

The minimum velocity of the silo roof is estimated without fluid dynamic drag. The minimum velocity for the 190 m flight is 43.2 m/s. The kinematic energy of the silo roof, E_2 is estimated with the weight of the roof, 10^4 kg.

$E_2 = 1 / 2 \times 10^4 \times 43.2^2 = 9.33 \times 10^6\ [J]$ (7)

The kinematic energy of the silo roof is 1.82 % of the increase of the internal energy of the gas in the silo.

Conclusion

The volume of the flammable mixture in the RDF silo is estimated about 5 % of the void volume of the silo. The weight of the RDF is 0.004 % of the total storage. To prevent the explosion, the overheated area has to be limited less that this ratio or all content in the silo has to be removed. The thickness of the flammable mixture layer is estimated less than 1 m. The effort of detection of flammable mixture from the roof section is difficult under the condition of the stable stratified motionless layer. The cooling of the surface of the RDF pile terminates the cellular convection in the silo and results the intake of the fresh air into the silo.

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