Development and Validation of Sodium Fire Codes

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Abstract

Development, verification, and validation of the spray fire code, SPRAY-3M, the pool fire codes, SOFIRE-M2 and SPM, the aerosol behavior code, ABC-INTG, and the simultaneous spray and pool fires code, ASSCOPS, are presented. In addition, the state-of-the-art of development of the multi-dimensional natural convection code, SOLFAS, for the analysis of heat-mass transfer during a fire is presented.

1. Introduction

Evaluation of the consequences of the sodium fires is one of the key issues in the designing and licensing of the fast breeder reactors. A leaked primary sodium releases radioactive materials into the containment atmosphere and may further into the environment. While, a secondary sodium leak in an air atmosphere produces large combustion heat resulting in temperature rises of the plant structures.

The spray fire code, SPRAY-3M, the pool fire codes, SOFIRE-M2 and SPM, and the aerosol behavior code, ABC-INTG have been developed. SPRAY-3M and SOFIRE-M2 have been coupled and integrated into the ASSCOPS code to analyze a simultaneous spray and pool fires.

Recently, development of a new best estimate code is underway by taking into account the recent advance in numerical techniques for multi-dimensional thermal hydraulics together with the recent findings on sodium fires.

This paper summarizes features of these codes and their validations.

2. Pool Fire Code

The SOFIRE-M2 code, that is currently widely used to analyze temperature and pressure transients during a pool fire, has been developed based on SOFIRE-2(1). With the code, a complicated heat structures around a pool, the reactions of sodium with oxygen and water vapor, and gamma heating by radioactive aerosols can be treated. Figure 1 shows its heat-mass transfer model. In the code, a set of ordinary differential equations are solved by the predictor-corrector technique.

Validation of the code has been carried out using results from the pool fire tests in the inert and air atmospheres. In the inert atmospheres, gas pressure and temperature transients agreed with test results within 20% (2). In the air atmospheres, the code agreed fairly well with results of the German KfK FAUNA F5 and F6 tests (3) assuming that 100% of the reaction combustion products is sodium peroxide.

Recently, the pool fire code, SPM, for an air atmosphere has been developed. In the code, assumptions are made that oxygen and sodium vapor are supplied to a flame over a sodium pool by convective mass transfer and vapor diffusion, respectively, while combustion heat is released into the atmospheric gas and transferred to a pool by convective heat transfer and conduction, respectively. Figure 2 shows the SPM sodium combustion model. SPM was validated using the above KfK FAUNA pool fire test results. Figure 3 shows the comparison between SPM ,SOFIRE-M2, and the tests.

3.Spray Fire Code

The SPRAY-3M code; an updated version of SPRAY-3, uses one-dimensional heat conduction equation to calculate temperature profiles within the cell walls and the floor. Figure 4 shows its computational model. Validation of the SPRAY-3M code has been carried out using results from the tests in a 21m^3 inert concrete cell containing 3% oxygen. Figure 5 shows the comparison between the code and the tests. It is seen that, although the calculated gas temperature is higher at the initial phase of a fire than that from the test, agreement is fairly well.

4.Spray and Pool Mixed Fire Code

For analyzing a simultaneous spray and pool mixed fire, the above two codes have been coupled and integrated into the ASSCOPS code. The code can analyze the temperature and pressure transients in such an event where a spray fire is going on in an upper cell while a pool fire is going on in a lower cell, as shown in Figure 6. Continuous sodium flow from the upper cell to the lower one can also be treated.

Validation of its pool model has been carried out for an air atmosphere using results from a pool fire test that has been carried out in the reinforced concrete test rig, SOLFA-1, in the SAPFIRE facility (4). As shown in Figure 7, agreement was fairly well. Differences between the code and the test results were 10% for sodium pool, gas, and wall temperatures, and 40% for the structural concrete.

5. Aerosol Behavior Code

In aerosol behavior code, ABC-INTG (5)(6), the following aerosol processes have been modeled.Gravitational, thermophoretic, and diffusional depositions and a ventilation or a leak to the adjacent cell are the aerosol removal terms. As aerosol agglomeration terms, Brownian, gravitational, and turbulent agglomerations. Figure 8 shows the model of the code. Recently, its numerical scheme was improved by introducing the sectional representation method proposed by Gelberd [7] to discretize the particle distribution. The improvement reduced computational time extensively keeping mass conservation of aerosol without losing numerical precision.

Validation of the code has been carried out using results from the large scale spray fire tests (8)(9). An example of the comparison between the code and the tests is shown in Figure 9. It was shown in such comparisons that the calculated results strongly depend on the gravitational collision efficiency. The benchmark calculation conducted under the auspices of EC (10) clearly indicated that the code predictions are in consistence with those of the major foreign codes, as shown in Figure 10. The code was used to evaluate the radiological consequences following the site evaluation accident as well as sodium aerosol release and transport following a sodium fire in the reactors.

6. Multi-Dimensional Convection Code

The codes presented are not able to consider explicitly the effect of space distribution of the physical variables that are of importance in evaluating the more precise heat-mass transfer processes associated with a fire. This leads to the following uncertainties. Firstly, although the codes use the same heat-mass transfer equation between the atmospheric gas and wall and between the gas and a pool, the equation has its own limitation, particularly, for a non-rectangular cell having a reactor component in which local heat-mass transfer rate may change from place to place due to complex atmospheric gas flow. Secondly, heat transfer processes between a pool and walls during a fire are radiation and convection where radiation heat transfer is strongly influenced by aerosol concentration. Usually, fraction of radiation heat transfer ranges from 40 to 60% in a vacant cell. Thus, without considering the spatial distribution of aerosol, realistic evaluation of radiation heat transfer can not be made.

To improve the situation, a multi-dimensional thermohydraulic code, SOLFAS, is under development by implementing K-epsilon turbulent model (11). Numerical scheme used is the SIMPLER method (12) by which a set of the discrete equations are solved. To calculate heat-mass transfer rates precisely at the vicinity of the wall and the sodium surface, only thermal conductivity and diffusivity of fluid instead of the experimentally fitted their correlations are used. With the code, spatial distributions of velocity and temperature of atmospheric gas and that of oxygen concentration and heat transfer to wall can be analyzed in the two-dimensional Cartesian coordinates. Figure 11 shows one example of the calculated results.

7. Conclusions

Development, verification, and validation of the spray fire code, SPRAY-3M, the pool fire codes, SOFIRE-M2 and SPM, the aerosol behavior code, ABC-INTG, and the simultaneous spray and pool fires code, ASSCOPS, are presented. In addition, the state-of-the-art of the multi-dimensional natural convection code, SOLFAS, for the analysis of heat-,mass transfer during a fire is presented.

For the pool and the spray fires, SOFIRE-M2 and SPRAY-3M have been, respectively, developed and validated. In the event of a pool fire in the air atmosphere, a flame is generated over a pool. SPM code ,therefore, has been developed and validated to consider this flame.

Validations of ASSCOPS, SOFIRE-M2, SPM, and SPRAY-3M have been carried out using results from the tests in the low concentration oxygen containing atmosphere and the air atmosphere.

ABC-INTG has been validated with the test results. The calculated results in the international benchmark test clearly indicated that the code results is in consistence with those of the other major codes.

Development of SOLFAS made it possible to analyze natural convective heat-mass transfer in turbulent flow conditions of the atmospheric gas.

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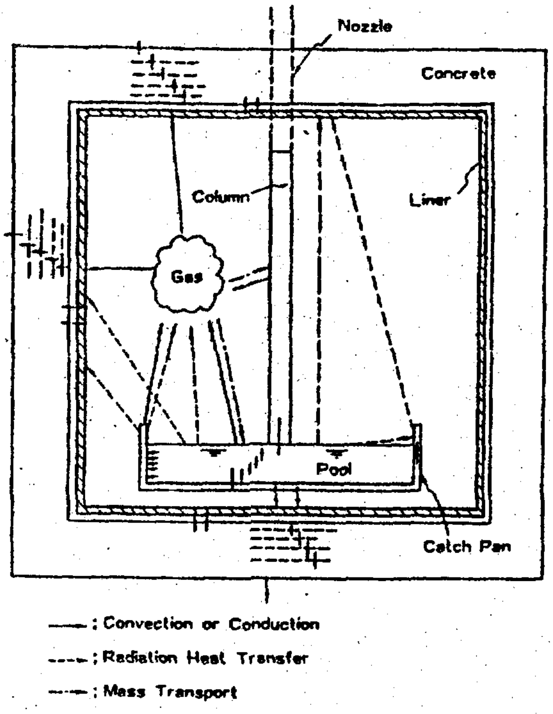

Fig. 1 Heat and Mass Transfer Model of SOFIRE-M2

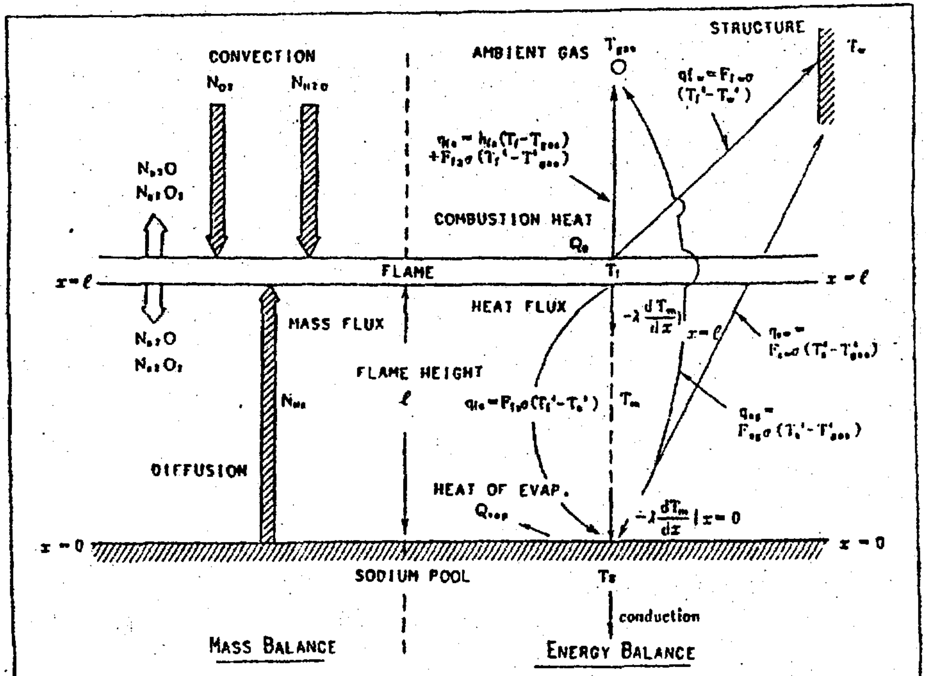

Fig. 2 SPM, Sodium Combustion Model

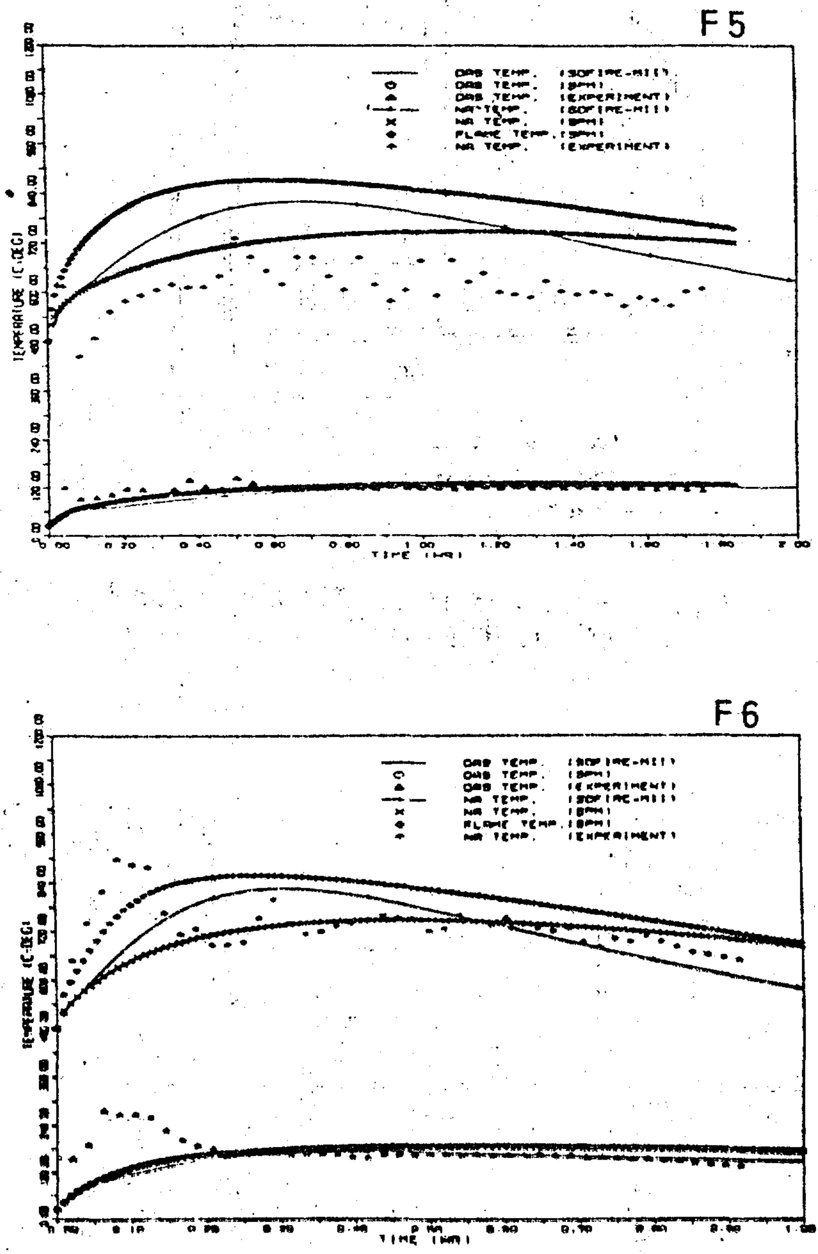

Fig. 3 Comparison between SPM, SOFIRE-M2, and Test Data

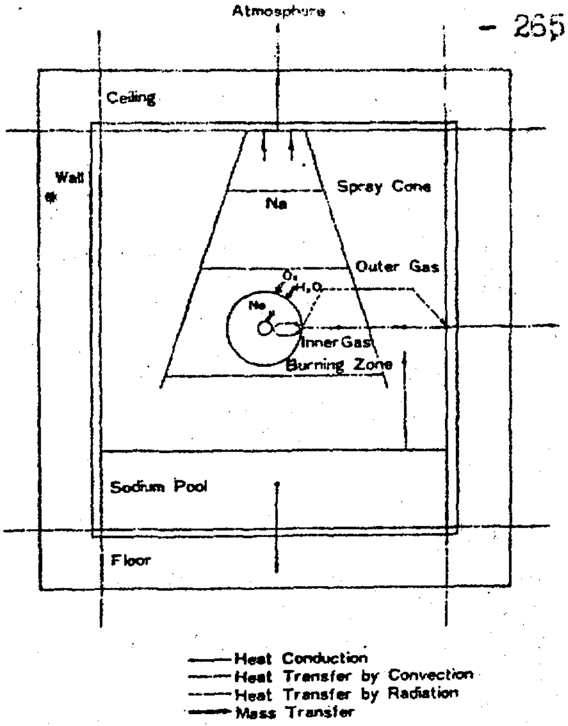

Fig. 4 SPRAY-Ⅲ M Computational Model

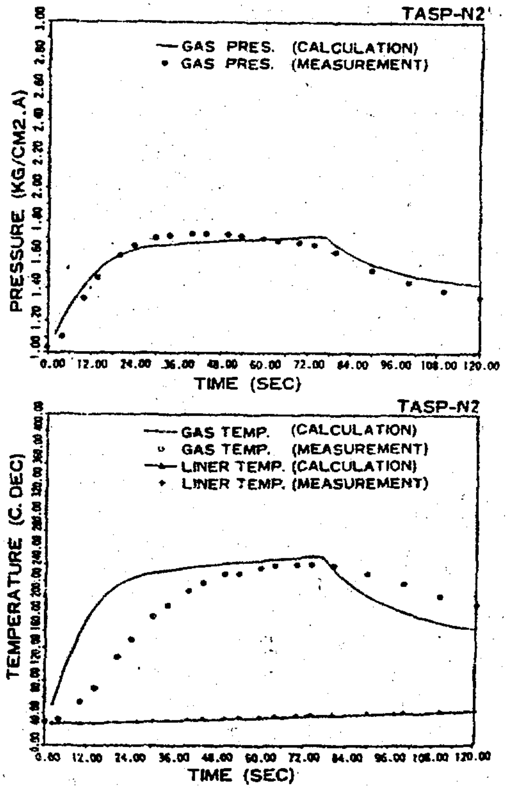

Fig. 5 Comparison between SPRAY-Ⅲ M and Test Results in Inert Atmosphere

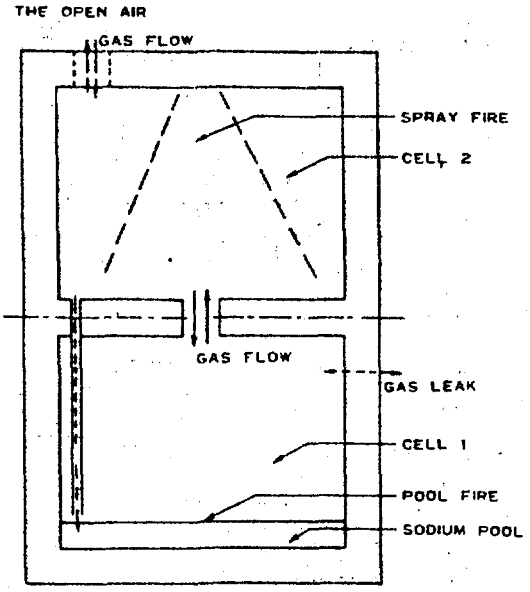

Fig. 6 Model for Spray Fire in One Cell and Pool Fire in Another Cell

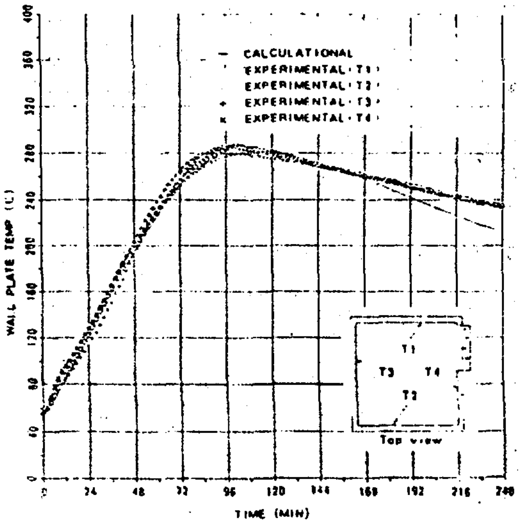

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Fig. 7 Comparison between ASSCOPS and Test Results in Air Atmosphere

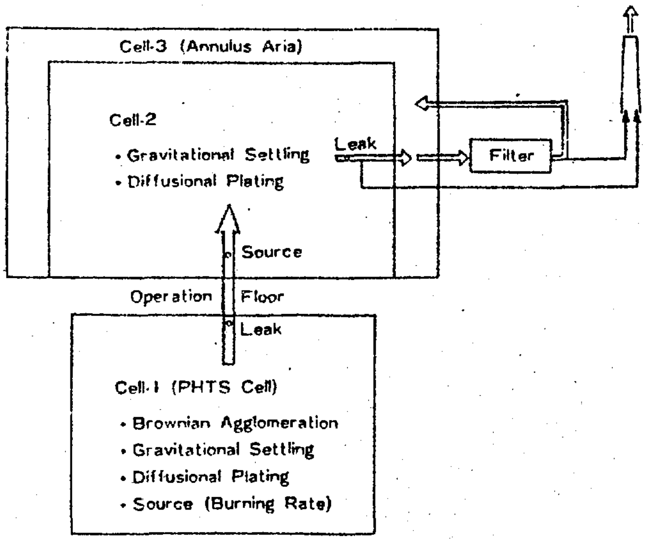


Fig. 8 Analytical Model of Aerosol Behavior

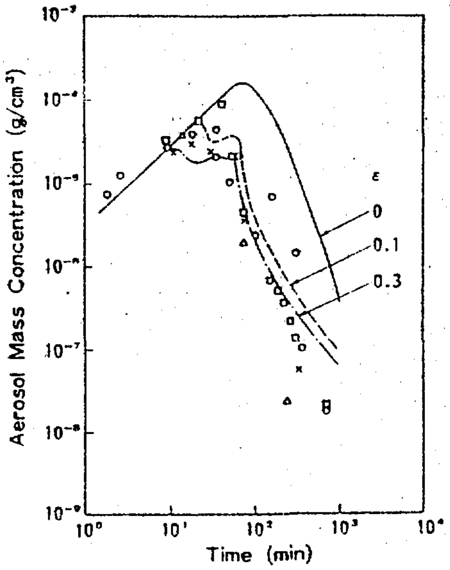


Fig. 9 Comparison between ABC-INTG and Test Results

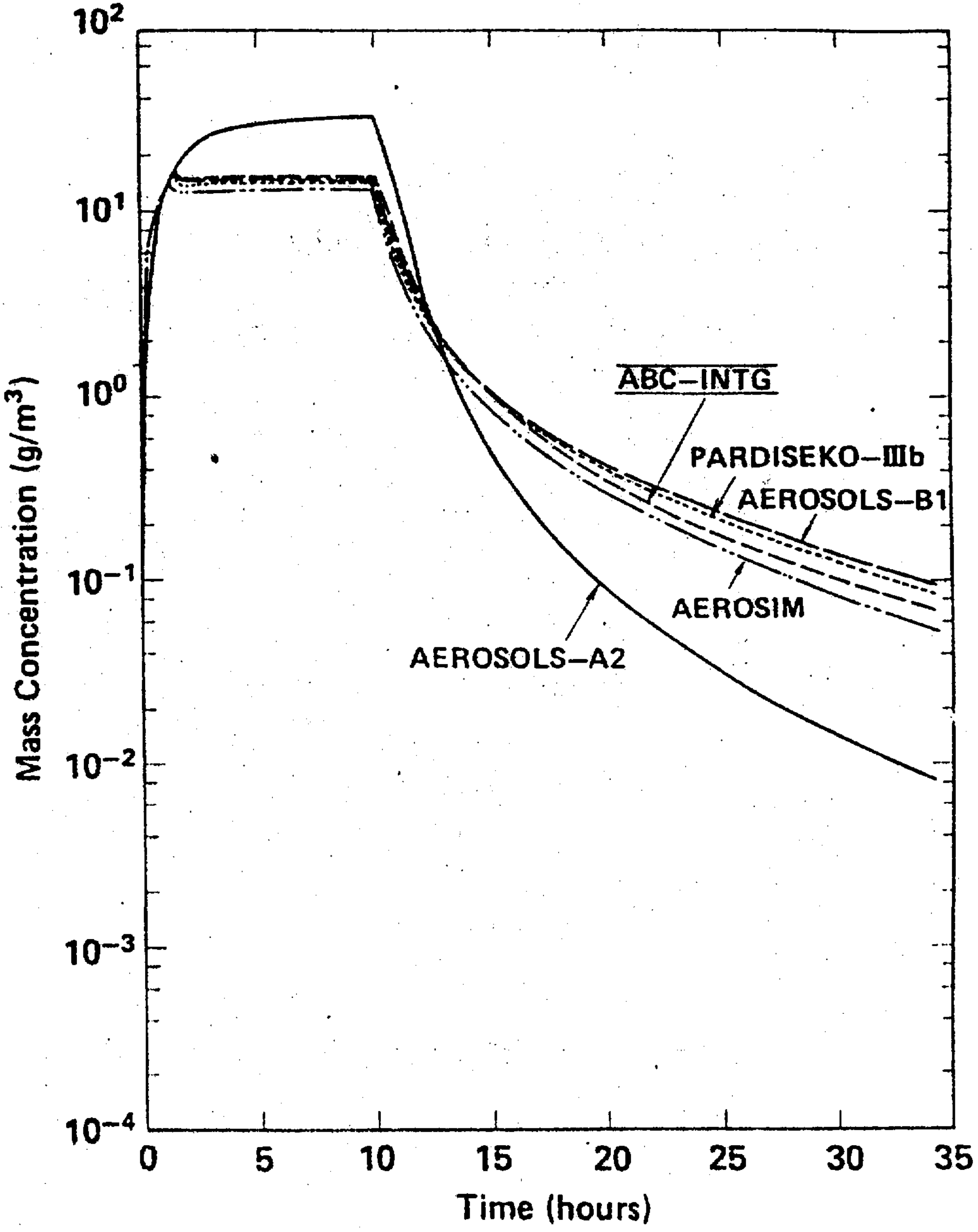
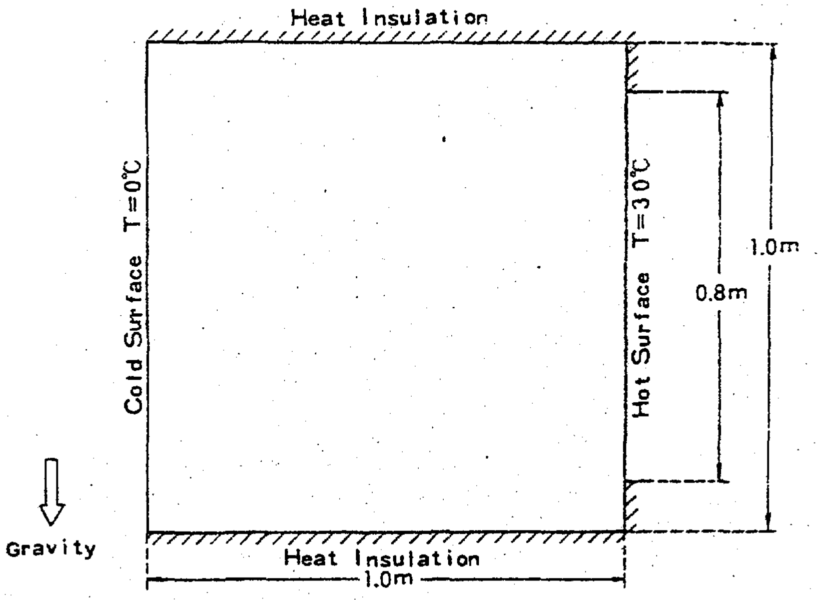
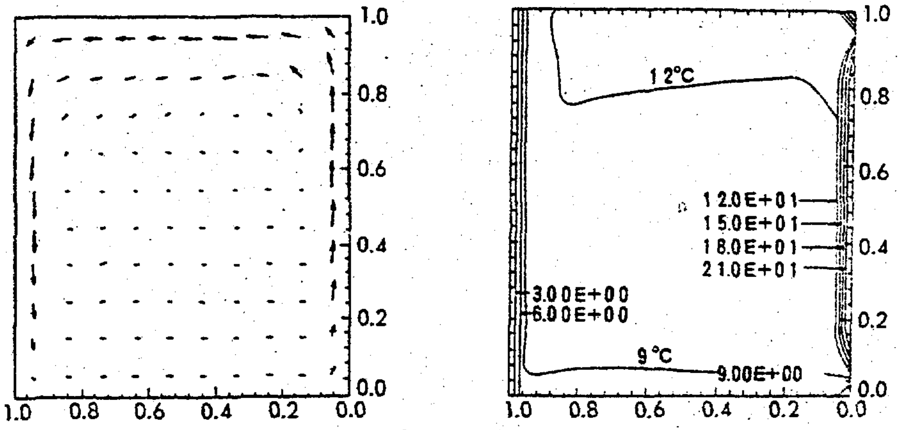


Fig. 10 Suspended Mass Concentration Reference Case (FUCHS-S=γ^2)



(a) Calculational Model



(b) Flow Pattern(10 minutes later) (c) Temperature Profile(10 minutes later)
$Pr=1$, $Gr \approx 10^5$ (mesh : 10×10)

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Fig. 11 Calculational Model and Flow Pattern