Numerical modeling of sodium fire – Part II: Pool combustion and combined spray and pool combustion

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HIGHLIGHTS

- A CFD based method is proposed for the simulation of sodium pool combustion.
- A sodium evaporation based model is proposed to model sodium pool evaporation.
- The proposed method is validated against sodium pool experiments of Newman and Payne.
- The results obtained using the proposed method are in good agreement with the experiments.

ARTICLE INFO

ABSTRACT

The risk of sodium-air reaction has received considerable attention after the sodium-fire accident in Monju reactor. The fires resulting from the sodium-air reaction can be detrimental to the safety of a sodium fast reactor. Therefore, predicting the consequences of a sodium fire is important from a safety point of view. A computational method based on CFD is proposed here to simulate sodium pool fire and understand its characteristics. The method solves the Favre-averaged Navier-Stokes equation and uses a non-premixed mixture fraction based combustion model. The mass transfer of sodium vapor from the pool surface to the flame is obtained using a sodium evaporation model. The proposed method is then validated against well-known sodium pool experiments of Newman and Payne. The flame temperature and location predicted by the model are in good agreement with experiments. Furthermore, the trends of the mean burning rate with initial pool temperature and oxygen concentration are captured well. Additionally, parametric studies have been performed to understand the effects of pool diameter and initial air temperature on the mean burning rate.

Furthermore, the sodium spray and sodium pool combustion models are combined to simulate simultaneous spray and pool combustion. Simulations were performed to demonstrate that the combined code could be applied to simulate this. Once sufficiently validated, the present code can be used for safety evaluation of a sodium fast reactor.

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1. Introduction

Liquid sodium is used as a coolant in sodium cooled fast reactors because it has excellent thermophysical properties. In particular, it has a high thermal conductivity, a low absorption rate of fast neutrons and a good fuel breeding performance. Moreover, it can be present in the liquid state in a wide range of temperatures. This enables liquid sodium to be used as a coolant.

However, liquid sodium is highly reactive when it is exposed to air or water, hence can be a potential fire hazard in a nuclear reactor. The leaked sodium essentially burns in two different modes, i.e., the spray and pool mode. Pool combustion continues for a long time in comparison to spray combustion and hence can have a more destructive effect on the equipments.

Several sodium leak and subsequent sodium fire accidents were reported in literature (Sathiah, 2013; Takata., 2007). For example, a sodium fire accident occurred on 8th December 1995 in Japanese Liquid Metal Fast Breeder Reactor (LFMBR) Monju, Tsuruga, Japan. Due to intense vibration, a pipe carrying sodium coolant cracked,

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Nomenclature

LFMBR   Liquid Metal Fast Breeder Reactor
CFD   Computational Fluid Dynamics
UDF   User Defined Functions
SOPA   Sodium Pool Fire Analysis
DO   Discreet Ordinate
PDF   Probability Distribution Function
JPDF   Joint Probability Distribution Function
$C_{p,g}$ gas mixture heat capacity at constant pressure [J/kg K]
t time [s]
a absorption coefficient of the gas due to the presence of aerosol particles []
D_f diffusivity [m^2 s^{-1}]
k_g gas mixture thermal conductivity [Wm^{-1} K^{-1}]
S stoichiometric ratio [·]
x_j coordinates in j-direction [m]
u_j velocity in j-direction [m/s]
S_m mass source term [kg m^{-3} s^{-1}]
g_i gravity acceleration [ms^{-2}]
f mixture fraction [−]
C_g constant [−]
H total enthalpy [J/kg]
S_h heat loss or gain [Wm^{-3}]
Y_j mass fraction of species j [−]
h_j enthalpy of species j [−]
C_{p_j} specific heat capacity of species j [−]
$\dot{m}$ mass evaporation rate [kg m^{-3} s^{-1}]
k_c mass transfer coefficient [ms^{-1}]
$Y_{f,s}$ mass fraction of sodium at the pool surface [−]
$Y_{f,\infty}$ mass fraction of sodium at the ambient [−]
Y_{O_2} mass fraction of oxygen [−]
$Y_{Na_2O_2}$ mass fraction of sodium dioxide [−]
Le Lewis number [−]
Pr Prandtl number [−]
Sc Schmidt number [−]
n constant [−]
M_f molecular weight of fuel species [g mol^{-1}]
M_g molecular weight of gas species [g mol^{-1}]
T_s surface temperature of the pool [K]
T_l liquid temperature [K]
Q_f total heat flux [Wm^{-2}]
H_{fg} heat of evaporation [J/kg]
T temperature [K]
L equivalent thickness of gas [K]
c_p heat capacity of liquid sodium [J kg^{-1} K^{-1}]
h heat transfer coefficient [Wm^{-2}]
h_l enthalpy of liquid [J kg^{-2}]
Pr_t turbulent Prandtl number [−]
$P_{f,s}$ saturation vapor pressure at pool surface [Pa]
P pressure [Pa]
c_2 constant [·]
B_s constant [·]
f_v volume fraction of aerosols [·]
P pressure [Pa]
ψ Pentagamma function [·]
λ_m reference wavelength [m]
ρ_a aerosol density [kg m^{-3}]
σ_s scattering factor [·]
ρ gas density [kg m^{-3}]
ρ_l liquid density [kg m^{-3}]
γ oxidizer-fuel coupling function [·]
α β-PDF parameter [·]

β β-PDF parameter [·]
μ_t turbulent viscosity [kg m^{-1} s^{-1}]
τ_{ij} viscous force tensor [Nm^{-2}]
σ_t turbulent Schmidt number [·]
ε turbulent dissipation rate [m^2 s^{-3}]
k turbulent kinetic energy [m^2 s^{-2}]
λ thermal conductivity of sodium [Wm^{-1} K^{-1}]
μ laminar viscosity [kg m^{-1} s^{-1}]
ε_i aerosol emissivity [·]

leading to a huge amount of sodium leaking on to the floor. The leaked sodium reacted with air thereby increasing the temperature, which resulted in melting of steel structures. The sodium reaction also produced caustic fumes because of aerosol formation. Since the sodium fire accident, Monju was shut down for about 15 years (IAEA-Tecdoc, 2007).

Several mitigation systems have been proposed in literature for example a Karlsruhe tray (Huber et al., 1975) and a leak collection tray (Diwakar et al., 2008, 2011) to catch leaking sodium and avoid its contact with air or water. Recently, a method for a suppression of sodium fires with liquid nitrogen is also proposed (An et al., 2013). However, further work on optimization of the design of such mitigation systems is necessary before these systems can be used in a sodium fast reactor.

To summarize, sodium leakages which lead to sodium reactions are dangerous for the safety of the reactor. Hence, sodium reactions must be avoided and therefore detailed experimental and numerical investigations of sodium reactions are important. In fact, understanding of sodium reactions with air and water is essential to develop computer codes, which can be used for the safety analysis of the reactor and to design mitigation systems.

Methods based on Computational Fluid Dynamics (CFD) are increasingly being used in modeling of sodium combustion. Methods based on CFD not only resolve all the spatial scales, but also simulate the physical processes governing a sodium pool combustion, e.g., turbulence combustion, turbulence-chemistry interaction, heat transfer, mass transfer, buoyancy, radiation and aerosol transport.

At NRG, our main focus is to develop a numerical tool based on CFD to simulate simultaneous sodium spray and pool combustion. We do this in three steps. In the first step, we develop and validate a code to simulate sodium spray combustion is described in Sathiah and Roelofs (2014). In the second step, we develop and validate a code to simulate sodium pool combustion. In the third step, we combine these codes to simulate simultaneous sodium spray and pool combustion and demonstrate the feasibility of our code. The second step is the major subject of this paper. Additionally, in the last section, we will demonstrate the feasibility of the third step i.e. the evaluation of the consequences of combined sodium spray and pool combustion in realistic situations.

In the past, both experimental and numerical studies on liquid sodium pool combustion have been reported in literature.

The SOFIRE code developed by Bergiger (1973) is based on a surface combustion model, it assumes that the flame temperature is the same as the liquid surface temperature and neglects the formation of a thin liquid vapor. Since the model neglects the vapor phase combustion, the flame temperature is underestimated, which leads to underestimation in the mean burning rate.

Sagae and Suzuoki (1985) proposed an analytical combustion model for sodium pool combustion. They claimed that sodium pool combustion essentially takes place in the vapor phase and the