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Numerical investigations of heat losses to confinement structures from hydrogen-air turbulent flames in ENACCEF facility

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ABSTRACT

In hydrogen safety analysis, structure response due to the pressure and thermal loads from the combustion is of great concern. It is of high significance to understand not only the combustion process itself, but also the heat losses from the combustion products to the solid structures which may have strong impacts on the pressure and temperature decays. In many previous numerical simulations, heat losses from turbulent hydrogen flames to the confinement structures were usually considered to be negligible or less important. However, it has been revealed by many experimental studies that modeling of heat losses from the combustion products is important for accurate predictions. Our objectives are to study the importance of various heat transfer mechanisms and their relative contributions to the total energy losses. Numerical investigations on the mechanisms of heat losses caused by propagating turbulent flames were performed using a semi-implicit pressure-based all-speed CFD code GASFLOW-MPI. Heat losses from turbulent sonic flames to the structures of the ENACCEF facility at IRSN were studied. It appears that the effect of heat losses on the flame propagation properties is not significant. However, the impacts of heat losses on the pressure peak and pressure decay after hydrogen combustions should not be neglected. It indicates from our simulation results that the convective heat transfer and thermal radiative heat transfer are the main contributors of the total energy losses to the structures of ENACCEF. In our cases, the effect of steam condensation heat transfer is relatively small but not negligible. The relative contributions of various heat transfer mechanisms could be different in other experimental facilities with various geometrical configurations, various internal structures, and various optical and thermal characteristics of the burnable gas mixtures. In general, it is suggested to include the heat transfer mechanisms in order to improve the reliability and accuracy of numerical analyses of hydrogen safety issues.

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Nomenclature

a_r	radiation constant
A	outward normal fractional area vector
As	cell face area for walls or the exposed area for internal structures
A_Z	constant coefficient in Zimont model
b	the velocity of the control surface S
c	speed of light
$C_{\varepsilon 1}$	constant coefficient
$C_{\varepsilon 2}$	constant coefficient
C_μ	constant coefficient
C_P	specific heat capacity
C_{p,h_2o}	specific heat of the water vapor at constant pressure
Da	Damkohler number
D_{eff}	effective molecular diffusivity
D_l	molecular diffusivity
D_t	turbulent molecular diffusivity
$\mathbf{D_d \cdot A}$	internal structure drag vector
h_d	mass transfer coefficient
h_d^*	corrected mass-transfer coefficient
hs	heat transfer coefficient
I_{H_2O}	specific internal energy of the water vapor
$\mathbf{J_\alpha \cdot A}$	mass diffusion flux vector
k	thermal conductivity of the solid structure
l_t	turbulent length scale
L_{ms}	mean beam length
$\dot{m}_s$	wall condensation or vaporization rate
n_{H_2O}	steam mole fraction
P_e	effective broadening pressure
P_{H_2O}	water vapor partial pressure
P_k	turbulent kinetic energy production by viscous stresses
P_{kb}	turbulent kinetic energy production by buoyant forces
Pr_t	turbulent Prandtl number
$p_{s,saturation}$	saturation pressure at the surface temperature
p_{sat}	saturation pressure
$\mathbf{q \cdot A}$	internal energy flux vector
q_i	radiation flux vector
$q_{s,conv}$	energy delivered to the structural surfaces by convection
$q_{s,cond/vap}$	energy delivered to the structural surfaces by steam phase change
R	flex ratio
Re_{wall}	wall Reynolds number
$S_{I,conv}$	source term of convective heat transfer
Sc_t	turbulent Schmidt number
S_I	source term of internal energy
S_L	laminar flame speed
S_m	source term of momentum
S_t	turbulent flame speed
S_V	source term of volume
$S_{\rho,\alpha}$	source term of species
S_ξ	source term of mean reaction progress variable
T	gas temperature
T_s	structural surface temperature
T_W	temperature inside the solid structure
u	velocity vector of the fluid
uc	a vector with the two wall tangential velocity components
u_{fric}	friction speed
u_*	wall shear speed
u^+	dimensionless velocity
U^r	radiation energy density
U_{tang}	velocity at the center of the first cell
y	distance to the surface
y^+	dimensionless wall distance
y_c	distance from the first cell center to the wall
Y_{H2}	mass fraction of hydrogen
$Y_{H2,initial}$	mass fraction of hydrogen before combustion
$Y_{H2,final}$	mass fraction of hydrogen after combustion

Greek symbols

á	thermal diffusivity of unburnt mixture
α_r	absorption coefficient
ε	dissipation rate of turbulent kinetic energy
ε_{r,H_2O}	grey medium total emissivity
ξ	mean reaction progress variable
Θ_m	mass transfer correct coefficient
κ	turbulent kinetic energy
λ	mean free path
μ_{eff}	effective viscosity
μ_l	molecular viscosity
μ_t	turbulent viscosity
ν	molecular kinetic viscosity
ρ_{H_2O}	water vapor density in the gas mixture
$\rho_{s,saturation}$	the saturation water vapor density at the structural surface conditions
σ	Stefan–Boltzmann constant
σ_b	constant coefficient
σ_k	constant coefficient
σ_ε	constant coefficient
ô$_c$	chemical time scale
ô$_s$	wall shear stress
ô$_t$	turbulent integral time scale
φ_{eff}	effective thermal conductivity
φ_l	thermal conductivity
φ_t	turbulent thermal conductivity
ϕ_T	rate factor for corrected heat-transfer coefficient.

Introduction

Hydrogen safety analysis has become one of the important tasks for nuclear safety engineers especially after the energetic hydrogen explosions occurred at the nuclear power plants at Fukushima Daiichi in 2011. Complex physical phenomena are involved in the nuclear reactor containment during the severe accident, such as flashing of water, turbulent flow, convection heat transfer, radiation heat transfer, steam condensation and evaporation, heat conduction in solid structure, hydrogen deflagration and detonation,