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Risk analysis of unburnt gas ignition in an exhaust system connected to a confined and mechanically ventilated enclosure fire

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ABSTRACT

The main purpose is to focus on the assessment of an ignition risk due to a large amount of unburnt fuel gases accumulated in the extraction duct connected to a confined and mechanically ventilated enclosure fire combining numeric and experiment. The current numerical study includes the initial well ventilated fire, spreading of flame in the enclosure, subsequent decay during under-ventilated conditions and exhaust of unburnt gas ignition in an extraction duct. Globally, Large Eddy Simulation (LES) combined with an Eddy Dissipation Concept (EDC) combustion model shows the feasibility for simulations of the air vitiation effect on transient combustion events occurring in a closed environment. A particular effort is undertaken to properly predict the pressure level inside a confined facility, and consequently, air inflow supply rate by using a HVAC system. Overall, the numerical results are in fair agreement with the experimental data for the minor species production (CO, H_2), and good agreement for pressure pulse, temperature peak, the major species and heat release rate. In spite of results for minor species that could be improved, the current work confirms the feasibility of a numerical treatment of under-ventilated fire phenomena. The possibility of simulating an ignition risk in an extraction duct connected to a very under-ventilated enclosure fire, has been demonstrated with success in medium-scale facility.

1. Introduction

The present study is motivated by the issue of the interaction between the ventilation system and the fire-induced pressure build-up in a confined facility. This problematic is typically encountered in the nuclear industry where the ventilation network ensures, in normal operating conditions, dynamic confinement in order to contain the potential release of radioactive material and avoid dispersion to the outside [1,2]. When a fire occurs in a confined facility, during its initial phase, the fire growths as long as it is fuel-controlled. Then the fire can become limited by the available oxygen and large amounts of unburned fuel gases can be generated from a condensed fuel on a scale where the heat flux is significant. Since fuel takes over from the oxygen in the enclosure, fire tends to extinguish, or reduce in intensity by oxygen starvation. The internal fire enters the decay phase, and the flame exhaust takes place. Fire in a progressively vitiated enclosure equipped with forced interconnecting ventilation system remains one of the key issues for ignition of combustible atmospheres composed of hot unburned gas in nuclear installations. Since substantial smoke spread can occur through ventilation systems, the mixing of the hotter smoke ($T > 200$ °C) with available oxygen in extraction duct can create a flammable mixture resulting in ignition. Intensive research has been carried over decades on the under-ventilated enclosure fire phenomenon [3–9], though, only a small proportion of the work has looked specifically on the ignition risk of unburnt gases in an exhaust system [10]. The work of Sinai [11] showed that for an under-ventilated enclosure, leakages and heat loss from wall have a major effect on the thermal stratification of the hot unburnt gas. Therefore, an ignition hazard analysis must takes into account the loss of dynamic confinement due to leakages and the possible mechanical damage of safety devices. The decision-making process regarding ignition safety assessment depends increasingly on numerical simulations. However, simulation of unburned fuel ignition is challenging due to the wide range of temporal and spatial scales involved as well as the size of detailed chemical kinetic mechanisms [12] – large hydrocarbon fuels conventionally used in industry comprise. There is currently no entirely tractable solution on the assessment of an ignition risk for engineering calculations.

For this study, a global approach was developed to predict the ignition risk in an exhaust system connected to a highly confined and mechanically ventilated enclosure during fire. An attempt to simulate several of the reduced well-confined mechanically ventilated fire

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Nomenclature

A_L	leakage area (m^2)
C_p	specific heat (kJ/kg K)
K	flow resistance coefficient
$\dot{m}_F$	fuel supply rate (kg/s)
$\dot{m}_A$	mass inflow rate of air (kg/s)
m	mass of control volume (kg)
H_{eav}	Heaviside unit step function
L	characteristic length of the enclosure (m)
s	stoichiometric coefficient
$\dot{Q}$	heat release rate (W)
T_m	bulk temperature of control volume (K)
T	temperature (K)
T_O	ambient temperature (K)
T_f	flame temperature (K)
u_{duct}	velocity in duct (m/s)
$\dot{V}_{fan}$	volume flow rate of the fan (m^3/s)
$\dot{V}_{max}$	free volume flow rate (m^3/s)
$\dot{V}_{leak}$	leak volumetric flow rate (m^3/s)
X_i	molar fraction of the species, i
Y_{O2}	mass fraction of oxygen
$Y_{O2,\infty}$	ambient mass fraction of oxygen
$Y_{O2,lim}$	critical value of oxygen concentration
Y_i	mass fraction of the species, i

Greek

τ_{mix}	key timescale (s)
$\dot{\omega}_i$	local reaction rate (kg/m^3 s)
ϕ	global equivalence ratio
ΔHc	heat of combustion (kJ/kg_fuel)
ΔHO	heat of combustion (kJ/kg_oxygen)
ΔP_{max}	stall pressure of the fan (Pa)
ΔP	downstream pressure difference (Pa)
ΔP_{nodes}	pressure difference between two nodes
ρ	density (kg/m^3)
ρ_a	air density (kg/m^3)
ρ_∞	ambient density (kg/m^3)

Acronym

EDC	Eddy Dissipation Concept
HVAC	Heating Ventilation Air Conditioning
LIL	Low Inflammability Limit
AIT	Auto-Ignition Temperature
ACPH	Air Change Per Hour
HRR	Heat Release Rate (W)

experiments in medium-scale using Fire Dynamic Simulator (FDS6) [13] will be done. A turbulent combustion model via four sequential, semi-global steps for the chemical reaction is used to obtain the key species. Quantitative comparisons on physical values are made between several computational results and measurements performed during a liquid pool fire scenario in a confined facility with forced ventilation.

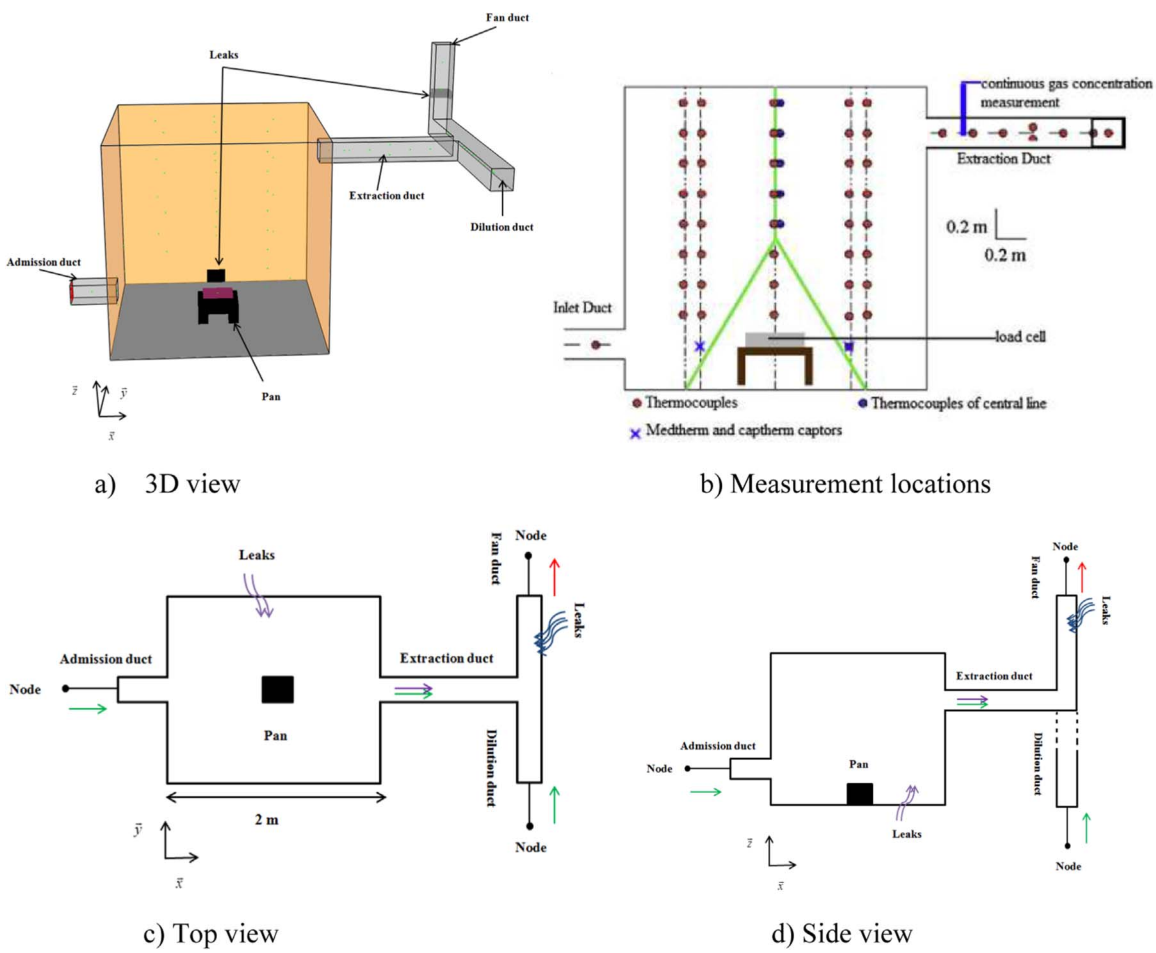

Fig. 1. Extraction duct connected to a confined and mechanically ventilated enclosure fire.