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Temperature and velocity distributions from numerical simulations of ceiling jets under unconfined, inclined ceilings

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ABSTRACT

Numerical simulations of ceiling jets under unconfined, inclined ceilings were conducted with the open-source code FireFOAM. A range of ceiling inclinations, 0–30° was considered with a 14 kW convective heat release rate (HRR) heptane fire used as the plume source, and the ceiling mid-point clearance from the top of the 0.228 m diameter burner kept fixed at 0.89 m. The predicted temperature and velocity in the developing ceiling jets were compared against the experimental data and empirical correlations. Temperature and velocity predictions on the elevated side of the ceiling are in general agreement with experimental data. Flow reversal in the lower side of the ceiling was predicted with good confidence, and comparison with experimental data was found to be reasonable. Following existing convention in the literature, the predicted results were non-dimensionalized using the convective HRR, ceiling height and radial distance from the ceiling mid-point. Comparison of the non-dimensional data on the elevated ceiling side showed better agreement for temperature against the correlation, whereas predicted velocity data showed a wider spread around the correlation values.

1. Introduction

Several concerns for industrial storage under inclined ceilings have been identified by the fire protection community. Possible delays in sprinkler activations due to the biased, upward flow of hot gases under the inclined ceilings cause the need for higher sprinkler densities resulting from larger fire size [1,2]. The primary aim of the present work is to numerically evaluate ceiling jet characteristics under inclined ceilings influencing sprinkler activation times and patterns. Besides storage occupancies, inclined ceilings are also present in tunnels, for which understanding of ceiling jet development related to smoke movement in inclined tunnel sections is an ongoing topic of research [3,4].

Large-scale suppression testing results with inclined ceilings are not readily available in the literature for sprinkler protection design [1]. Few small- and intermediate-scale tests have been conducted in the past to investigate inclined ceilings. Vettori [5] investigated residential sprinkler activations in compartment fire scenarios involving ceiling inclinations of 0°, 13° and 24°. Kung et al. [6] conducted small-scale tests with pool fires measuring ceiling jet velocities and temperatures for ceiling heights of 0.28–0.89 m and ceiling inclinations of 10°, 20° and 30°. Floyd et al. [7] reported intermediate-scale test data on the performance of residential sprinklers with ceiling heights of 2.7–5.7 m and inclinations of 18.4° and 33.7°. Bill and Hill have also reported residential sprinkler response in manufactured homes with a ceiling height of 2.1 m and inclination of 10° [8]. The majority of the above mentioned studies involved use of residential sprinklers and compartment or tunnel fire scenarios, generally with weak plume sources.

In recent years, Oka and co-workers have invested considerable effort in characterizing ceiling jet temperature and velocity characteristics under inclined ceilings. Among several publications, of relevance to the present study are two investigations on unconfined, inclined ceilings [9,10]. Oka et al. [9] investigated ceiling jets under ceilings inclined between 10° and 40° with ceiling heights, H, of 1.0 m and 1.5 m using heptane and methanol diffusion flames in the HRR range of 7.6–43 kW. The study provided temperature data and the authors modified existing horizontal ceiling correlations [11] for application to inclined ceiling jets. Oka and Ando [10] extended the previous study by recording particle image velocimetry (PIV) data for velocity measurements. Detailed comparisons of measured temperature and velocity data with additional proposed correlations were also included in the study.

Due to the excessive cost of large-scale testing, numerical modeling becomes an attractive tool for the investigation of inclined ceiling flows, provided that the models are used within their limitations. A few numerical modeling studies have been conducted in the past with respect to inclined ceilings. Vettori [5] applied an earlier version of the Fire Dynamics Simulator (FDS) [12] to predict sprinkler activation

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Nomenclature

b_c	plume half width (m)
C_p	heat capacity (kJ/kg-K)
g	gravitational acceleration (m/s^2)
H	ceiling clearance (m)
k_{sgs}	subgrid kinetic energy (m^2/s^2)
ℓ_p	ceiling jet penetration distance (m)
$\dot{Q}_c$	convective heat release rate (kW)
r	radial distance along ceiling slope (m)
ΔT	excess temperature (K)
ΔT_c	plume centerline excess temperature (K)
ΔT_{max}	max ceiling jet excess temperature (K)
T_∞	ambient temperature (K)
v_θ	ceiling jet velocity (m/s)
V_{max}	max ceiling jet velocity (m/s)
w_c	plume vertical velocity (m/s)
$\widetilde{Y}_F$	fuel mass fraction (dimentionless)
$\widetilde{Y}_O$	oxidizer mass fraction (dimentionless)
z	vertical distance (m)Greek
Δ	LES filter size (m)
ε_{sgs}	subgrid dissipation rate (m^2/s^3)
ν_t	turbulent viscosity (m^2/s)
$\dot{\omega}_F'''$	fuel consumption rate (kg/m^3-s)
$\bar{\rho}$	mean density (kg/m^3)
ρ_∞	ambient density (kg/m^3)
τ_m	turbulent mixing time (s)

times for growing fires under inclined ceilings with a maximum heat release rate (HRR) of 1.1 MW. Floyd et al. [7] applied FDS modeling with a 300 kW fire and compared predicted ceiling jet temperatures with test results. In a recent study, Carlsson [13] has used FDS modeling to predict sprinkler activations under inclined ceilings. The study highlights the issues involved with modeling the inclined ceilings using a "sawtooth" mesh. Methods of mitigating the issue of vorticity generation at the sharp corners of the ceiling mesh resulting in adverse effects on the flow predictions were discussed; however, the "sawtooth" mesh was retained for the sprinkler activation predictions.

A study on the effect of ceiling inclination on sprinkler activation patterns and spray transport was recently conducted [2]. As part of the study, a computational fluid dynamics (CFD) investigation of inclined ceiling jets was made to validate the FireFOAM code [14] before application in large-scale, rack-storage fire driven sprinkler activation simulations. The present study provides a detailed analysis of temperature and velocity characteristics from the simulation results. Predictions were compared against experimental data from the literature for unconfined, smooth ceilings.

2. Numerical model

The FireFOAM code [14], which is based on the open source framework OpenFOAM [15], is used in the current study. Models for large eddy simulations (LES) of buoyant turbulent diffusion combustion, thermal radiation heat transfer, solid-phase pyrolysis, and wall heat flux are included in FireFOAM for fire growth simulations (Ref [16] includes FireFOAM modeling references). Flows under horizontal ceilings have also been simulated, and temperature and velocity predictions in the ceiling jet have been close to the experimental data [16]. A response time index (RTI) model [17] has been included in FireFOAM, and has been verified to give accurate estimates of sprinkler activation. In the present study, the combustion, turbulent flow and radiation models are used to simulate the fire plume and the resulting ceiling jets. FireFOAM version 2.2.x [14] has been used for the simulations.

The FireFOAM code solves fully compressible, three-dimensional reacting Navier-Stokes equations with the finite volume technique on unstructured grids [15]. Conservative forms of equations for continuity, momentum, sensible enthalpy and species transport are solved with the PISO algorithm applied for pressure-velocity coupling. The eddy dissipation model (EDM) [18] is applied for combustion modeling. The fuel consumption rate, $\dot{\omega}_F'''$, in the EDM is modeled as

$$\widetilde{\dot{\omega}_F'''} = c(\bar{\rho}/\tau_m)\min[\widetilde{Y}_F, \widetilde{Y}_O/s], \tag{1}$$

where, c=4 (see Section 3.2.1 in Ref [18] for details), τ_m is a turbulent mixing time, $\widetilde{Y}_F$ and $\widetilde{Y}_O$ are the filtered mass fractions of fuel and oxidizer, respectively, and s is the stoichiometric oxygen to fuel ratio. The turbulent mixing-time is estimated as

$$\tau_m = k_{sgs}/\varepsilon_{sgs}, \tag{2}$$

where k_{sgs} and ε_{sgs} are the subgrid scale (SGS) kinetic energy and its dissipation rate, respectively. Transport of subgrid kinetic energy is included for turbulence closure. The SGS turbulent viscosity, ν_t, in the momentum equations is computed from the solution of k_{sgs} as described in Fureby et al. [19]. The dissipation of k_{sgs} is modeled as

$$\varepsilon_{sgs} = c_\varepsilon k_{sgs}^{3/2}\Delta^{-1} \tag{3}$$

following Fureby et al. [19]. The constant $c_\varepsilon = 1.048$ and Δ is the LES filter size [19]. The turbulent viscosity is computed as

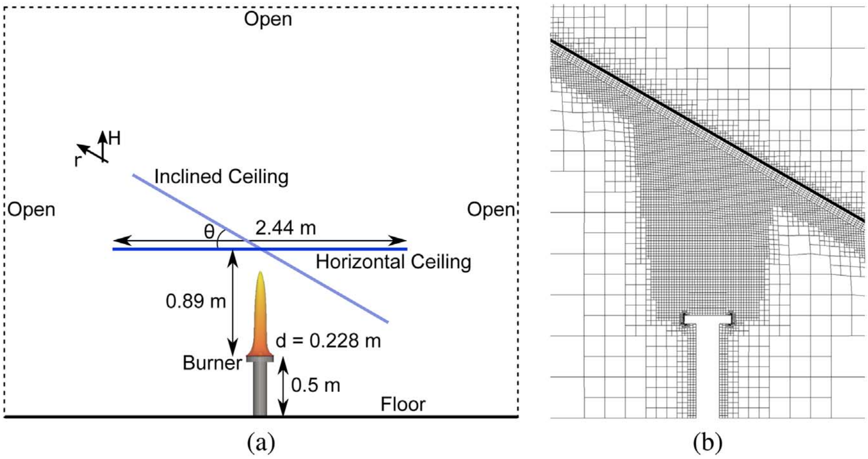

Fig. 1. Computational setup used in the study showing (a) a horizontal and an inclined ceiling at θ angle located 0.89 m above a 0.228 m diameter burner (elevated by 0.5 m), and (b) a close-up image of the refined sections of the computational mesh for a 30° inclined ceiling case.