Predicting Detector Response Time Using Saltwater Modeling on Sloped Ceilings

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Abstract
A scale-modelling study was carried out on a ceiling jet flowing along an unconfined sloped surface with angles ranging from horizontal to 40 degrees. A quantitative saltwater modelling technique, utilizing laser diagnostics, was applied to visualize the flow. Measurements were taken using multiple planar laser sheets around the plume impingement region to form a two-dimensional map of flow parameters along the surface of the sloped ceiling. Front arrival times were also calculated for each configuration at specific locations. The measured data, including the density difference and velocity along the sloped ceiling, were locally estimated along with the front arrival time to determine the response time for a virtual heat detector or sprinkler head mounted on the ceiling.

Keywords: Saltwater, Sloped Ceiling, Laser Diagnostics, Detector Response

Introduction
Determining the activation time of both fire detection and suppression equipment is a critical step in the design of fire safety systems within buildings. While there is a large existing knowledge base for the transport of smoke and hot products along ceilings in large compartments, there are few studies that approach the problem of sloped ceilings [1]. Recent studies have performed numerical simulations of these sloped ceiling configurations in warehouses, however both experimental and numerical modeling of these flows has been limited.

Here, an approach using saltwater modeling, which draws on an analogy between buoyant smoke transport and an inverted plume of saltwater in a large freshwater tank, is utilized to model potential detector response in large compartments with sloped ceilings. As fire detection and suppression equipment activate based on either the concentration of smoke or heating by the near-wall flow, it is possible to use the collected data to develop estimates of response times in a potential fire scenario.
Velocity and density difference profiles of the ceiling jet are therefore collected from experimental measurements and applied to a detector response model by Heskestad [3-5] in this work. This approach is similar to that applied by previous work using models for a ceiling jet (for instance by Alpert [6,7]), however this work is unique in that it is applied to sloped ceilings which have different upslope, downslope and radial behavior that are captured in experiments.

**Experimental Approach and Setup**

Inverse quantitative saltwater modelling was utilized to simulate the ceiling jet flow originating from a turbulent buoyant plume impinging on an unconfined sloped ceiling. The technique relies on saltwater (simulating a fire plume), being denser than fresh water (simulating the fresh air), impinging onto an upside-down “inverse” configuration consisting of an angled plate residing in a large freshwater tank. The similarity between the governing conservation equations in their dimensionless forms for fire and saltwater sources [5], coupled with advanced laser diagnostics, enables the use of a scaling concept to represent the fire in terms of quantitative dimensionless field data (i.e. saltwater density difference and velocity). This approach is ideal as it has been proven to accurately model smoke movement in both buoyant plumes and along complex ceiling geometries [8-10]. Because the technique can rapidly be applied to complex building configurations without the drawback of grid resolution encountered in computational fluid dynamics (CFD), many configurations can be tested with essentially infinite grid resolution for both study and numerical validation. As a demonstrative exercise, the activation time of simulated detectors will be assessed using the data obtained from experimental measurements.

Particle Image Velocimetry (PIV) was used to provide measurements of the flow field of the particle-seeded plume as it entrains fresh water and travels along the sloped ceiling. Planar Laser Induced Fluorescence (PLIF) measurements were also taken to measure the salt concentration, directly related to the scalar field (density and temperature), via the saltwater modelling analogy [8]. The experimental setup is depicted in Figure 1 (Left), while a schematic of the laser diagnostics used is provided in the centre and a close up of a resulting PLIF image is shown in Fig. 1 (right). A 30 mJ double-pulsed 532 nm wavelength Nd:YAG laser by New Wave illuminated the test volume and a ProX 4M-CCD camera with 2048×2048 (4 M pixels) spatial resolution by LaVision collected the images at 5 Hz by means of the LaVis 7.2 software-DAQ system. The laser was equipped with an array of two cylindrical lenses mounted on top of the laser head. The first lens turned the circular 1.5 mm diameter laser beam into a laser sheet for planar measurements, while the other lens was able to adjust the thickness of the laser sheet. For PIV, the saltwater source was seeded with 50 µm diameter PSP Polyamide particles the laser was set to a double pulse mode where the camera
recorded one image per pulse, with a known time between the pulses \((dt)\). The velocity field could then be estimated by tracking the displacement of the particles. The PLIF technique relies on the intensity of the fluorescence of Rhodamine Rh-6G dye, which was diluted into the source and excited by laser illumination, thus exhibiting quantitative density-difference measurements. The camera detected the exhibited fluorescence from the excitation of the plume into the plane created by the optics and determined the saltwater plume local density. For PIV, the camera mounted a high-pass 532 nm filter for the particle scattered light, while for PLIF, a 540 nm cut-off filter captured the higher wavelengths exhibited by the Rh-6G fluorescence spectrum.

Results

Results are presented first with a focus on describing the flow behavior of a ceiling jet generated along a sloped ceiling. The inverse saltwater modeling approach is then used to determine the front arrival time, \(t^{*}_{FA}\) for a “single-planar” imaging approach along the centerline and later extended to a “multi-planar imaging” grid to locally estimate both arrival and lag times.
Analysis of a sloped ceiling jet necessitates knowledge of the flow behavior close to the surface of the sloped ceiling, where temperature and velocity gradients are used as inputs into correlations for flow behavior. Figure 2 shows measurements of the velocity field along the centerline close to the surface of the sloped ceiling for a virtual detector located at $S_{+1}=16$ cm from the plume impingement point. The flow is well resolved in this region, revealing both the boundary layer close to the surface which eventually reaches a maximum, followed by an exponentially-decaying plume region along $S_3$. The distribution is thought to depend on the increase in buoyancy of the ceiling jet with the slope along the upward direction which accelerates the flow.

Figure 3 shows the front arrival time, $t_{FA}^*$, defined as the time from the start of the experiment to the time when the gradient of the density difference is the maximum, e.g. the moment when the front of the plume reaches the sensor location. In Fig. 3 a single planar laser sheet along the centerline is shown, however measurements are also taken radially both spanwise and streamwise from the center, where the front arrival time is found to vary with distance from the impingement point. The upper portion of Fig. 3 shows a sequence of instantaneous PLIF realizations captured 16 cm downstream from the impingement point along the upward slope of the plate. The images provide insight on the evolution of the ceiling jet flow at different angles.
As the slope is increased, the density at the front of the jet increases because of poor mixing with the fresh water and reduced entrainment. The component of gravity aligns with the flow as the slope increases, attaching the plume and boundary layer closer to the surface.

Based on the similarity between a saltwater source and a fire induced ceiling jet flow, this preliminary result translates into useful information on the hazards in a real fire scenario. A higher density difference for steeper slopes translates in higher temperatures and higher heat fluxes near the ceiling, thereby introducing potential structural integrity problems and faster activation of sprinklers or detectors. In addition, the lower part of Fig. 3 shows the dimensionless front arrival time \( t^{*}_{FA} \) based on the scalar \( \theta^{*}_{sw} \) along \( t^{*} \) for a virtual smoke detector located 16 cm downstream from the impingement point. The exact arrival time was determined at the instance when the dispersion quantities were seen to rise most rapidly (steepest slope), before the flow attained a steady state along the ceiling. The information here is presented in a dimensionless form consistent with the results from the previous saltwater research conducted on both smooth and beamed ceilings [8, 11]. Table 1 summarizes both dimensionless and dimensional arrival times for comparison.

Table 1. Front arrival time from the release of the saltwater source.

<table>
<thead>
<tr>
<th>Slope [deg.]</th>
<th>0</th>
<th>24</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{FA} ) [s]</td>
<td>15.2</td>
<td>32.2</td>
<td>39.4</td>
<td>46.4</td>
</tr>
<tr>
<td>( t^{*}_{FA} ) [-]</td>
<td>1.3</td>
<td>2.8</td>
<td>3.3</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Figures 4 and 5 show representative density difference maps under the sloped ceiling surface for 0 to 40 deg. slopes (Fig. 5) and the methodology applied to obtain results (Fig. 4). The isocontour lines were determined by probing the ceiling jet flow in both the streamwise ($S_1$) and spanwise ($S_2$) directions over the plate.

![Fig. 4. Density difference $\theta_{sw}$ distribution map: measurement point grid over the plate (Above); density difference contour lines for 0, 24, 30 and 40 deg. slope (Below).](image)

Figure 4 shows a grid of 81 measurement points obtained where both streamwise and spanwise laser sheets cross the same location and by assuming mean dispersion and velocity values at a distance of 4 mm from the ceiling for each point (geometrically consistent with the possible location of a detector or fire suppression device). Within a 4 cm x 10 cm cell formed between intersecting measurement points (Fig. 4), a grid of mean values was generated by interpolating data along $S_1$ and $S_2$ direction to mm resolution, starting from the measured points at the intersections between laser sheets. The density difference distribution of radial (0 deg.) or of elliptical shape (24 and 30 deg.) was observed for low angle slopes, while the distribution changed and expanded to a round egg-like shape for a steeper ceiling slope (40 deg.).

Local dimensionless saltwater quantities were estimated to predict the detector response time ($t_{act}$), which consisted of the front arrival time ($t_{FA}$) and detector lag time ($t_{lag}$). The dimensionless front arrival time ($t_{FA}^*$) was first determined at each location, following the approach outlined in Fig. 3 and then interpolating between measured locations. The dimensionless detector lag or response time ($t_{lag}^*$) was used to determine a generic detector response time ($t_{act}^*$) using Heskestad’s detector model [2, 11],

$$t_{lag}^* = \frac{\theta_{sw}^*}{d\theta_{sw}^*/dt} + \frac{L_d/L_{sw}}{u^*},$$

where $d\theta_{sw}^*/dt$ is the dimensionless rate of change of the saltwater concentration, simulating smoke from a real-scale fire. The characteristic length, $L_{sw}$, was chosen as the distance between the injector outlet and the plume impingement point on the plate (~34 cm) and the geometric entrance resistance length, $L_d$, was 1.5 mm, following previous work on
flat ceilings [2,11]. The sum of the dimensionless front arrival and lag time, both estimated at each location, provide the dimensionless response or activation time for a virtual detector. A generic detector is shown in this work as a demonstration of the capabilities of saltwater modeling, however future work could incorporate specific ionization smoke detectors [2] or heat or thermal detectors (e.g. sprinklers) with modified response models.

Fig. 5. Density difference $\theta_{sw}$ distribution map: contour lines for 0 (a), 24 (b), 30 (c) and 40 (d) deg. slope.

The results here are displayed as isocontour lines in Fig. 6 for 0, 24, 30 and 40 deg. slopes. The time isocontours show the time needed for activation starting from the moment a plume impinges the plate. The plume rapidly propagates over the ceiling in both $S_1$ and $S_2$, with relatively good symmetry with respect to the $S_2$ axis.
Times are shown here in seconds, however dimensionless times could be applied to different geometries in order to estimate times at larger scale for sloped ceilings at various angles.

Fig. 6. Activation time $t_{\text{act}}$ (in dimensional form) distribution map for 0 (a), 24 (b), 30 (c) and 40 (d) deg. slope.

Discussion & Conclusions

This study has shown how saltwater modelling can be used to study the activation time of detectors or fire suppression devices on a sloped ceiling. Calculation of both time of plume arrival and activation time was accomplished by using a gridded series of laser sheets which captured saltwater concentrations and velocities. This provides valuable information as to the effect of slope that may be reduced to simplified models useable as a critical design tool. As expected, by increasing the slope, the activation times progressively tended to skew to the upslope direction and a delay in the activation time was found for the downslope locations of the plate, mainly due to a decrease in the front arrival time in that region. Similar patterns were found for the 30 and 40 deg. slopes, while a large difference was observed in the transition from flat to 24 deg. scenarios. Further tests should investigate slopes between these two scenarios, which may further reveal the transition between 0 to 24 deg.
References


