Autodesk CFD for Fire and Smoke Simulation

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About the speaker

Dr. Munirajulu. M

22+ years industry experience in CFD analysis
Speaker at AU 2017, Las Vegas
Using Autodesk CFD Simulation for MEP design
Focus areas: Data Center Cooling, Basement Car Park Ventilation, DG room ventilation, Smoke simulation in buildings
Life Safety
Key Objectives
Key Learning Objectives

AT THE END OF THIS SESSION, YOU WILL BE ABLE TO:

• LEARN HOW FIRE AND SMOKE IS MODELED
• VISUALIZE AND HIGHLIGHT KEY RESULTS
• GAIN INSIGHT INTO MAKING GOOD DESIGN DECISIONS
• UNDERSTAND BENEFITS AND LIMITATIONS
Back to Basics….

Before we jump into the fire modeling using CFD, let us look at some basics

• Fire triangle/ tetrahedron
• Stages of fire
• How does fire spread?
• Effects of fire
• Hot smoke and life safety
• Smoke contaminant and life safety
• Loss due to fire
Fire Triangle

Controlled fire

https://en.wikipedia.org/wiki/Fire_triangle

The Fire Triangle Explained!

The Fire Tetrahedron Explained!

Fire Tetrahedron

Uncontrolled fire

Author: Neil P. Tilley (mbifm) (Tech IOSH)
Stages of fire

- **Ignition**: Fuel, oxygen and heat join together in a sustained chemical reaction.
- **Growth**: With the initial flame as a heat source, additional fuel ignites. The size of the fire increases and the plume reaches the ceiling.
- **Fully developed**: Fire has spread over much of fuel; temperatures reach their peak.
- **Decay (burnout)**: The fire consumes available fuel, temperatures decrease, fire gets less intense.
Fire spread

\[ \dot{q} = \frac{kA(T_{\text{Hot}} - T_{\text{Cold}})}{L} \]

Conduction

https://www.nist.gov/%3Cfront%3E/fire-dynamics
Fire spread

\[ \dot{q} = h(T_{Hot} - T_{Cold})A \]

Convection
Fire spread

\[ \dot{q} = (\varepsilon \alpha T_{Hot}^4) A \]

Radiation
Effects of uncontrolled fire

- Human loss
- Structural damage
- Material damage
- Disruption of work
- Financial losses
# Hot smoke and life safety

## What does temperature do? Burning from heat

<table>
<thead>
<tr>
<th>°C</th>
<th>°F</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>98.6</td>
<td>Normal human oral/body temperature</td>
</tr>
<tr>
<td>44</td>
<td>111</td>
<td>Human skin begins to feel pain</td>
</tr>
<tr>
<td>48</td>
<td>118</td>
<td>Human skin receives a first degree burn injury</td>
</tr>
<tr>
<td>55</td>
<td>131</td>
<td>Human skin receives a second degree burn injury</td>
</tr>
<tr>
<td>62</td>
<td>140</td>
<td>A phase where burned human tissue becomes numb</td>
</tr>
<tr>
<td>72</td>
<td>162</td>
<td>Human skin is instantly destroyed</td>
</tr>
<tr>
<td>100</td>
<td>212</td>
<td>Water boils and produces steam</td>
</tr>
</tbody>
</table>

[https://www.nist.gov/%3Cfront%3E/fire-dynamics](https://www.nist.gov/%3Cfront%3E/fire-dynamics)
Smoke contaminant and life safety

What does smoke do? Suffocation to death

Figure A. Shares of Fire Deaths by Smoke Inhalation or Burns

- Smoke inhalation and burns
  - 2003-2007 death certificates: 23%
  - 2004-2008 NFIRS national estimates homes: 45%
  - 1994-1998 death certificates: 0%

- Smoke inhalation only
  - 2003-2007 death certificates: 40%
  - 2004-2008 NFIRS national estimates homes: 51%
  - 1994-1998 death certificates: 5%

- Burns only
  - 2003-2007 death certificates: 26%
  - 2004-2008 NFIRS national estimates homes: 25%
  - 1994-1998 death certificates: 5%

- Other
  - 2003-2007 death certificates: 10%
  - 2004-2008 NFIRS national estimates homes: 2%
  - 1994-1998 death certificates: 2%
1,342,000 fires were reported in the U.S. during 2016.

- **3,390** civilian fire deaths
- One civilian death occurred every 2 hours and 35 minutes
- **14,650** civilian fire injuries
- One civilian injury occurred every 34 minutes
- **$10.6 billion** in property damage
- A fire department responded to a fire every 24 seconds

*based on 2016 property loss estimates*
Modeling Fire and Smoke for Retail Shopping Mall
Fire safety strategy

Engineering based approach to fire safe design

• Automatic fire detection (Smoke & heat detectors) - beam detectors in atrium/skylight areas and point type detectors in occupied areas

• Automatic alarm system

• Automatic fire sprinkler system for fire suppression

• Exit signage

• Smoke control – make up air and smoke extract fans

• Egress – available safe egress time based on NFPA 101
Fire safety strategy

• Smoke zones - designed to restrict smoke from spreading from one smoke zone to another

• Fire detection system - zoned identical to the smoke zones, including all visual and audible fire alarms.

• Fire sprinkler system - zoned similar to the smoke zones and vice versa throughout the building.
Design requirements based on:

- National Building Code (NBC 2005) of India
- NFPA 92 B - Standard for Smoke-control systems (2012)
- BS PD 7974-6:2004
General practice of smoke simulation

Flow only enters and leaves through the bottom and top surfaces. The main flow direction should be to the vertical.

Gap underneath the fire for cool air to be drawn in.
Retail shopping mall

CAD geometry for CFD
Sectional details of Retail mall

Sectional outputs from CFD at X and Y Plane

Fresh Air Entry

Fire Location

UG Level

G+1 level

G+2 level – (PODIUM LEVEL WITH FANS)

G+2 level

ZONE 1

ZONE 2

ZONE 3

ZONE 4

ZONE 5
Sectional details of Retail mall

G+2 level
G+1 level
UG Level

Fire Location
Material properties

Air

• Variable quantity, to account for density variation with temperature and buoyancy
Fire modelled as a short cylinder and assigned as resistance material. Steel ring around the fire part (~1/2 flame height) and suppressed from the mesh.

Use free area ratio = 0.85 and conductivity of 200 W/m-K to spread the heat within the flame.
Fire Part

**Fire**  : Fast t- squared fire growth up to 2500 kW and steady state thereafter is considered (with quick response sprinkler).

Fire diameter = 3.35 m (NFPA 92B, A.5.2.1, based on HRRPUA 568 kW/m² and fire size of 5 MW). Variation of fire size with respect to time. Fire size reaches 1.75 MW (convective portion of 2.5 MW) at 210 seconds. Convective portion is taken as 70% of the total fire HRR.
Boundary conditions- air domain inlet

- Temperature
  - Type: Temperature
  - Unit: Celsius
  - Time: Steady State
  - Spatial Variations: Constant
  - Temperature: 35.2
  - Static / Total: Static

- Pressure
  - Type: Pressure
  - Unit: Pa
  - Time: Steady State
  - Pressure: 0
  - Gage / Absolute: Gage
  - Static / Total: Static

- Scalar
  - Type: Scalar
  - Time: Steady State
  - Scalar: 0
Boundary conditions - outlet

West side of fans is considered to be switched off.

Only the East side of the fans is assigned for flow rate boundary conditions in Zone-2.

<table>
<thead>
<tr>
<th>Fan Number</th>
<th>Fan size (CFM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42420</td>
</tr>
<tr>
<td>2</td>
<td>39600</td>
</tr>
<tr>
<td>3</td>
<td>46650</td>
</tr>
<tr>
<td>4</td>
<td>42420</td>
</tr>
</tbody>
</table>
Mesh details

The fire and the air above and below - good uniform mesh - to capture the flow accurately by CFD.

Solid ring suppressed from the mesh and ensures that flow only enters and leaves through the bottom and top surfaces.
**Initial conditions**

Air domain set at initial conditions as scalar=0, temperature =35.2°C
• Transient: Switched ON (set to run for 20 minutes)
• Results quantities: Visibility ON
• Smoke visibility parameters:
  o Extinction coefficient: 37000 ft²/lb
  o Illuminated sign = 8
• Soot Particle yield: 0.05 (for fuel package of wood and polyurethane foam)
Solver settings

- Flow and Thermal -- On
- Gravity set to 1 in the downwards direction
- Advanced
  - General Scalar on
  - Diffusion Coefficient
    - $2 \times 10^{-5}$ m$^2$/s
- Turbulence: Switched ON; k-epsilon Turbulence

Smoke spreading is:
- momentum-driven
- actual diffusion coefficient less critical.
Key Results
for Final Design
What is important from CFD analysis for designers and regulators

Information about

- Smoke movement
- Temperature distribution
- Airflow field

Smoke transport is tracked w.r.t rise of smoke in atrium, along corridors and interconnected spaces
Most important key results:
Smoke free space and tenable smoke temperature

Based on BS PD 7974-6:2004, Annex G

• Smoke tenability limit - 10m visibility, Table G.1

• Temperature tenability limit - 60°C, Table G.3

• Toxicity is deemed acceptable if visibility >10m
Smoke development
Smoke visibility (Smoke free space) – X Plane

At time = 30 sec
At time = 1 min
At time = 3 min
At time = 6 min
At time = 10 min
At time = 19 min

1.8 m level line from G+2 Floor
Smoke development
Smoke visibility (Smoke free space) – Y plane

- At time = 30 sec
- At time = 1 min
- At time = 3 min
- At time = 6 min
- At time = 10 min
- At time = 19 min

1.8 m above G+2 FFL
1.8 m level line from G+2 Floor
Smoke development
Smoke visibility (Smoke free space)- @ 1.8 m level from G+2 floor (Z-plane)
Key result 1: Smoke visibility-10m (smoke free space)

Walking corridor space is smoke free (smoke free clear height of 1.8m above the corridor floor)

Smoke visibility @ 19 minutes – 1.8 m level from G+2 floor (Z-plane)

1.8m above FFL
Temperature development

X Plane

At time = 30 sec

At time = 1 min

At time = 3 min

At time = 6 min

At time = 10 min

At time = 19 min

1.8 m level line from G+2 Floor
Temperature development
Y Plane

At time = 30 sec

At time = 1 min

At time = 3 min

At time = 6 min

At time = 10 min

At time = 19 min

1.8 m level line from G+2 Floor
Key result 2: Tenable smoke temperature

In G+2 floor below 1.8m FFL, smoke temperature is below 600°C and hence tenability limits for smoke temperature is not breached up to 20 minutes from start of fire.
Airflow field development
Z Plane (at UG level above fire location*)

At time = 1 min

At time = 3 min

At time = 4 min

At time = 5 min

At time = 15 min

At time = 20 min

m/s
Air speed development
Y Plane

Fresh air being drawn by the smoke plume at UG, G+1 and G+2 levels

m/s
Key result 3: Air flow field

• Fresh air velocity contacting smoke plume has not exceeded 1.02 m/s. Hence smoke plume does not get dispersed and rises as plume above required smoke free clear height.

• Replacement air velocity at entrance to the shopping mall does not exceed 1.6 m/s and hence does not hinder people escape through the entrance.

The incoming airflow through escape doors should not exceed 5 m/s to permit unimpeded escape. BS 7974-2:2002, Clause 9:5
Outcome for final design

- Well defined plume development and smoke rising towards smoke exhaust fans
- Make up air does not disturb the smoke plume – no smoke dispersion and visibility problems
- Hot smoke temperature is within acceptable limits for human safety.
- Smoke visibility is within acceptable limits for safe evacuation

**Bottom line:** Smoke exhaust fan capacity and layout is adequate to provide smoke free space for about 20 minutes for the final design
Insights from CFD analysis for good design decisions
Challenges in design ..

• building geometry is large and complex
• a prior distribution of smoke/ air velocities is not known
• prescriptive code provides only guidance
• a number of scenarios for ventilation fan layout and capacities are possible

So to arrive at the final design, we had to analyze few design variants and results for the initial design and final design are compared leading to a adequate and good design....
Initial Design (2 smoke zones)

Final Design (no. of smoke zones revised)

Podium | Fans size (CFM)/Qty
---|---
A | 42420/2 nos
B | 46650/2 nos
C | 39600/2 nos
D | 42420/2 nos
E | 34100/2 nos

Fan Number | Fans size (CFM)
---|---
1 | 42420
2 | 39600
3 | 46650
4 | 42420
Optimize smoke exhaust system design.

Helpful tool

Estimate smoke exhaust volume flow rate based on:

• fire size
• outdoor ambient temperature
• distance from base of fire to smoke layer interface

Also we can estimate:

• minimum edge-to-edge separation
• maximum number of fans
• maximum flow through each fan to avoid plug holing

Ref: AtriumCalc Version 1.1

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Comparison of smoke visibility

Initial Design

At time = 30 sec

At time = 1 min

At time = 2 min

At time = 3 min

Final Design

At time = 30 sec

At time = 1 min

At time = 2 min

At time = 3 min

1.8 m level line from G+2 Floor
Comparison of smoke visibility

Initial Design

Final Design

At time = 4 min

Z plane - 1.8m level above G+2 floor

At time = 4 min

At time = 10 min

At time = 10 min
Comparison of smoke temperature

Initial Design

At time = 3min

Final Design

At time = 3 min

1.8 m level line from G+2 Floor
Comparison of Airflow field

Initial Design

Final Design

At time = 2 min

1.8 m level line from G+2 Floor
Comparison of Airflow field

Initial Design

Average velocity is 3.5 m/s
Average velocity is 5 m/s
Average velocity is >1.02 m/s
Z Plane (UG level) at time = 10 min

Final Design

Average velocity is 1.4 m/s
Average velocity is 1.6 m/s
Average velocity is 0.8 m/s
Fire Location

Y Plane at time= 10 min

Y Plane at time= 20 min
Optimize smoke exhaust system design: summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Design</th>
<th>Final Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke movement/Smoke visibility</td>
<td>Not good/ Not acceptable</td>
<td>Good/ Acceptable</td>
</tr>
<tr>
<td>Smoke temperature</td>
<td>Risky</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Air flow field</td>
<td>Not acceptable</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Smoke exhaust system design and layout</td>
<td>Not suitable</td>
<td>Adequate</td>
</tr>
</tbody>
</table>
What do we conclude and recommend?

Based on a given smoke exhaust fan layout and fire zoning logic, Autodesk CFD analysis can accurately predict:

- smoke development
- smoke movement
- visibility levels and temperature distribution.

**Hence this approach can be used to make good design decisions to minimize smoke hazards.**
More examples

Airport – Baggage reclaim area

Convention Center – Exhibition Hall
Benefits and Limitations
Benefits

• Easy to use
• Quick validation of smoke control strategy
• Engineering based approach to fire safety measures (performance based)
• Interface with Revit so CAD model to CFD model is easy
• More insight leads to better design decisions
Limitations

• Transient solution requires small time step so run time is long –many hours
• Scalar for smoke generation (=1) instead of generation rate (Kg/s) as input
• Uncertainty in smoke particulate yield values
• Tenability for fire brigade –radiation from the smoke layer simulation-challenge
• Limited verification of smoke model
How did I do?

- Your feedback is valuable
- AU speakers get feedback in real-time
- Fill out a class survey using AU mobile app.
- Your feedback results in better classes and a better AU experience.
Thank you for listening….

Keep in touch!

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For info on who we are and what we do…

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