SEQUENTIAL POSITIVE PRESSURE VENTILATION FOR HIGH-RISE FIRES

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Abstract- Positive Pressure Ventilation (PPV) is a firefighting tactic that can mitigate the spread of fire and the combustion products to improve the safety of firefighters and civilians in wind-driven high-rise fires more than without PPV. In complex high-rise structures with multiple stairwells, the efficacy of PPV operation is greatly influenced by the fire location, fan deployment tactics, ventilation and fire-attack points which can drastically change the fire behavior. This paper describes a simulation-based study to analyze the influence of these parameters on the performance of PPV operation in complex high-rise structural fires. The results obtained provide qualitative trends for the effectiveness of PPV with respect to concerned parameters and establish the guidelines for sequentially ventilating the heat and smoke to reduce the thermal hazards to firefighters.

Keywords- Fire Prevention and Safety; Fire Department of New York City (FDNY); Modeling, Simulation, and Optimization of Firefighting Procedures; Positive Pressure Ventilation.

I. INTRODUCTION

Wind-driven fires in high-rise building present one of the most dangerous environments that a firefighter can face. With the increasing concentration of high rise buildings, development of new firefighting procedures and review of existing firefighting techniques is the necessity for today's fire service. In the last week of February 2008, the New York University – Polytechnic School of Engineering (NYU-Poly), the National Institute of Standards and Technology (NIST), and the Fire Department of New York (FDNY) conducted 14 burn experiments at a seven-story abandoned high-rise building on Governor's Island, NY. The main goal of these controlled burn experiments was to test the efficacy of three different firefighting procedures (PPV, Wind Control Device Deployment, and High-rise Nozzles) in improving firefighter safety, and to establish a better understanding of how to control the flow of heat and smoke in wind-driven high-rise fires. The results of the burn experiments evaluated each of the firefighting tactics individually as well and in conjunction with each other to assess their benefit to firefighters, and provided the baseline understanding of wind-driven high-rise fire behavior. In last few years, FDNY has implemented these tactics in several real-life high-rise fires in New York.

While the experiments proved that the tools and tactics were effective, firefighters needed to understand how to implement the tactics in buildings and under conditions outside the test parameters. In real-life, the parameters (wind speed, control of doors, number of fans, fan positions fire location etc.) that influence the performance of PPV vary to a greater extent. Given the high cost and limited opportunities for full-scale burn tests, duplicating the experimental conditions and conducting multiple burns for parametric analysis is challenging. Computer simulation techniques were used to address this requirement and the effectiveness of PPV has been established for a simple prototype structure with single typical stairwell in previous publications by the authors.

In this paper, PPV effectiveness has been analyzed in a complex real-life structure with one single typical stairwell and one scissor type stairwell where its efficacy can vary greatly with respect to fire location, fan location, ventilation and fire-attack points, sequence of venting tactics, and PPV operation can be very confusing for rescue firefighters. Here, PPV has been studied using on-field PPV tests and Fire Dynamics Simulator (FDS 5.0) for various possibilities of fire scenarios. When firefighters deploy these new tactics in time-critical stressful fire-situations, the understanding of the trends of performance of PPV depending on these parameters is more important than the exact numerical data describing variations for each particular situation. Additionally, establishing the accurate quantitative data for every random real-life fire scenario that involve many unknown parameters can be very complex for firefighters to understand and may not be used by the fire service. Therefore, the focus of this study is to establish the qualitative trends for performance of PPV in complex high-rise structural fires under the influence of concerned parameters and their relative impact on the fire-rescue operation. Thus, the present study is of paramount interest to the firefighting community as it can be used to modify current standard operating procedures. The academicians and researchers can quantify each trend in detail for numerous other possibilities.

II. ON-FIELD TESTS

In PPV operation, a positive pressure zone is created inside the stairwell by directing a significant amount of airflow into the stairwell by the deployment of specially designed fans at the entrance of stairwell (and / or other appropriate locations of the stairwell). The static pressure created by PPV fans must be greater than that created by spread of fire so that PPV fan deployment can drive away the flow of smoke, heat, and other combustion products.

With the help of FDNY officials, on-site PPV tests were conducted at modern large residential high-rise structure (73 x 20 x 65 m) in Brooklyn, New York. This 7 story building has one single typical stairwell (6.9 x 2 m), one scissor type stairwell (6.9 x 2 m) and one long public hallway (73 x 2 m) connecting all apartments on every floor. Several PPV fans (BD27-H-9.0 by Tempest Technology) were used to provide the influx of air at the rate of approximately 24,000 CFM (i.e. 11.23 m^3/s) into the stairwell and create positive pressure zone. Detailed specifications of PPV fan are available in manufacturer's sheet.

In order to reduce the requirement of computational time and memory for simulation-based analysis, it was assumed that the fire is located on sixth floor. Please note that, in North America, ground floor is considered as the first floor and same terminology will be used in this paper. Several scenarios of PPV tactic were considered for this fire.
The fan was always placed at 3 feet (0.9 meter) away from the stairwell door in a way that its horizontal axis is parallel to the ground. In order to measure the pressure level created by PPV operation, the differential pressure sensors were placed on floor 2, 5, and 7.

The high port of differential sensor was exposed to the pressure inside the stairwell and the low port of the sensor was exposed to the atmospheric pressure via flexible tube. The positive pressure levels achieved in these scenarios are provided in Table 1 and compared with those from simulation-based analysis.

III. SIMULATION –BASED ANALYSIS

Fire Dynamics Simulator (FDS 5.0) is a free computation fluid dynamics software developed by National Institute of Standards and Technology (NIST) of the United States Department of Commerce. This Fortran program reads input parameters from a text file and numerically solves a large eddy simulation form of the Navier–Stokes equations appropriate for low-speed, thermally-driven flow to mainly investigate and analyze the smoke and heat transport from fires.

The outputs from FDS are displayed using Smokeview, a free visualization program provided by NIST. This numerical program requires an input with respect to "what" and "how" a fire burns.

In this study, this was achieved by providing the thermo-physical properties of the fuel load involved in the fire and by describing the events such as windows failure, opening / closing of doors, activating PPV fans, deploying WCDs, etc.

FDS is well-established simulation software that provides valuable insight into how a fire may develop, spread and react to the surrounding conditions.

The ability of this program to accurately predict the fire behavior has been previously evaluated by full-scale experiments where FDS predictions were found to be well-within the experimental uncertainty.

The simulation-based study described in this research paper is mainly focused towards how fire in a high-rise structure react and how the efficacy of PPV tactic changes in response to several parameters that are of paramount interest to the firefighting community.

IV. MODELING

FDS 5.0 allows only rectilinear meshing of the objects. Therefore, a number of minor construction details found in real-life high-rise buildings cannot be addressed and were not considered in this study. Moreover, the purpose of this study is to analyze the performance of PPV for a standard structure-configuration, fuel-load, environmental conditions, and deployment tactics that can be used to generalize and establish guidelines.

Hence, considering the computational cost, a simplified 3-dimensional model of high-rise stairwells was developed based on the dimensions and layout of the structure mentioned in Section II and is shown in Fig. 1 and 2.

The seven-story building model consists of one single typical stairwell, one scissor type stairwell, and a long public hallway.

The stairwell consists of eight landings with a door on each floor, the topmost door being the bulkhead (roof) door. Each floor consists of a stairwell door leading to a public hallway that connects to all apartments.

The apartment door opens into the living room which is connected to kitchen, bedroom, and restroom. There is a double window (2 x 1 m) in living room and a single window (1 x 1 m) in bedroom.

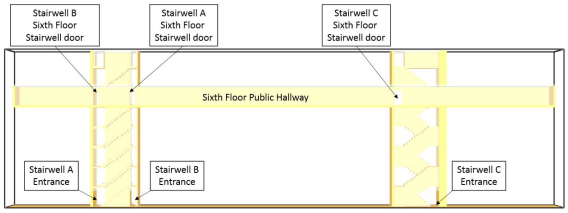


Fig. 1. 3 Dimensional model of the structure (Front View)

Table 1. Comparison between on-site PPV tests and PPV simulation results

PPV Strategy	Stairwell	On-Site Test Pressure Readings (Pa)			Simulation Pressure Readings (Pa)		
		Floor# 2	Floor# 5	Floor# 7	Floor #2	Floor #5	Floor #7
1. One PPV fan at first floor	A	28	23	16	31	25	19
	B	32	26	18	32	25	19
	C	29	25	20	30	24	20
2. Two PPV fans at first floor (parallel combination)	A	41	36	26	44	36	29
	B	38	34	26	42	36	28
	C	41	34	29	42	34	28
3. One fan at first floor and second fan at third floor	A	32	31	23	33	30	24
	B	33	28	22	33	31	22
	C	30	28	20	32	29	22

The apartment has a typical fuel load that consists of common furniture items such as a bed, TV, sofa, wooden chairs. Table 2 and 3 describes the thermo-physical properties of their materials adopted from the available literature . As the fuel load in every real-life fire varies to a greater extent, one may argue the selection of furniture, its material and properties. But all simulations conducted in this study have exact same fuel load with same orientation and structural configuration. Therefore, these approximation and assumption should not introduce an error in the qualitative trends for performance of PPV established in this study.

V. PPV SIMULATIONS

FDS only allows rectilinear meshing which causes limitations on modelling the circular geometry of PPV fan. There are several papers in the literature which discuss PPV tactic and how to model the PPV fan within FDS using higher grid resolutions and tremendous computational power. These studies analyze the PPV effects in near field and the computational domain considered in those studies is much smaller than the domain of entire high-rise building needed to be considered in this study. Moreover, when PPV is used to fight fires in a high-rise structure, velocity effects on the upper floors are negligible. For high-rise fires, PPV's static pressure in far field which drives the smoke and heat away from the firefighters is more important, and should not be affected significantly by the approximation of a small (in comparison to the building and stairwell size) circular fan surface to a squared fan surface of same area (0.5 m^2). Therefore, in order to save the computational time and cost, and considering the number of fire scenarios to be simulated for this study, PPV fan was considered as a square surface 3 ft (0.9 m) away from the stairwell door that provides the influx of air at the rate of approximately 24,000 CFM (i.e. 11.23 m^3/s) into the stairwell.

Considering the crawling motion of firefighters during the search-rescue operation on fire floor, static pressure sensors were modelled at the mid-level of floor / apartment height (i.e. 1.3 m above the floor level) in the middle of stairwell. Grid convergence test was performed by simulating the same scene several times with increasing number of cells. The mesh was refined until the recorded values at all locations stabilized and difference between the recorded values became negligible with increasing mesh resolution. The model used for all simulations in this study has uniform rectilinear mesh that includes 1,890,000 total number of cells and each cell has equal volume of 0.0088 m^3.

The floors, ceilings, surfaces of furniture, walls, stairwell steps and all other solid surfaces of the structure were assigned as wall boundaries. Windows, doors were simulated by creating time-dependent holes in the surfaces. The computational domain which is initially occupied with atmospheric air at 25^0C has open boundary conditions in all directions except the ground.

In order to validate the 3D FDS model, on-site PPV tests are simulated first and results are compared in Table 1. Please note that, in several research studies, it has been well-established that the placing fans behind each other (series combination) cannot be effective as volume of air entering the stairwell does not change [8, 9]. Therefore, the series combination of PPV fans is not investigated in this study. Additionally, the bulkhead door was closed in both approaches to maintain desired pressure levels.

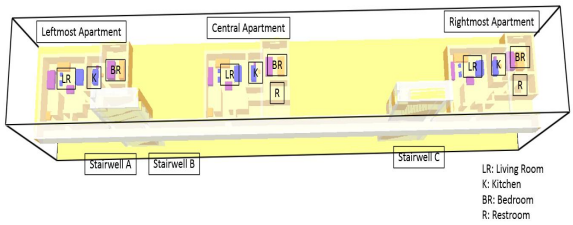


Fig. 2. 3 Dimensional model of the structure (Top View)

Table 2. Thermal properties of materials

Material	Ignition Temperature (^{0}C)	Heat Release Rate (kW/m^2)	Thermal Conductivity (W/m.k)	Thermal Diffusivity (m^2/s)
Pine	390	200	0.14	8.3e-8
Upholstered Cushion	370	700	0.20	1.2e-6
Polystyrene	420	500	0.30	1.1e-7
Gypsum Board (Walls)	400	100	0.48	4.1e-7

The results obtained from on-site tests and PPV simulations were found to be in close agreement with each other which helped to validate the 3D model. It can be observed that two PPV fans at first floor (strategy 2) can create better positive pressure zone inside the stairwell to drive away the combustion products more effectively. Therefore, this strategy will be used and tested with the fire scenes described below.

VI. FIRE SIMULATIONS

A simple timeline of fire events was considered to determine the most efficient considerations for attack and ventilation tactics.

Although, the unplanned sequence of random events in real-life fires may be much more complex than the timeline followed in this study, the proposed timeline is sufficient to optimize the ventilation and attack points for PPV tactic in structure with multiple stairwells which is the main focus of this study.

In a PPV tactic, attack stairwell is the stairwell at which PPV fan is deployed and positive pressure zone is created so that firefighters can stretch the hoseline. Ventilation stairwell can be one of the other stairwells (other than attack stairwell) that can be used to vent the heat and smoke in public hallway for better thermal conditions and visibility for rescuing firefighters.

It was assumed that the fire ignites in bedroom of apartment on sixth floor and the apartment door was left open by the occupants. Stairwell doors and bulkhead doors were initially closed. As the fire continues to grow, at 120th second, windows failure occurs inside the apartment that allows wind (10 miles per hour or 16 km/h) to enter inside the apartment and spread the heat into public hallway. At 180th second, a firefighter opens the sixth floor door of the attack stairwell.

Item	Quantity	Material	Size (m)
Bed	1	Upholstered Cushion	2x2.5x1
Single Sofa	4	Upholstered Cushion	0.75x0.5x0.5
Double Sofa	2	Upholstered Cushion	1.5x0.5x0.5
Chairs	8	Pine	0.5x0.5x1
Table	2	Pine	1x0.5x1
TV	1	Polystyrene	0.5x0.5x0.5

Table 3. Fuel load in each apartment

At the same moment, another firefighter opens the sixth floor stairwell door and bulkhead door of one of other two stairwells which act as ventilation stairwell. The simulation was stopped after another 70 seconds (at 250th second), which should be enough time for firefighters to be prepared and enter the fire floor with the hoseline through attack stairwell.

The temperature variations inside the structure were monitored and recorded by creating five thermal sensor points. Considering the crawling motion of firefighters during the search-rescue operation on fire floor, these thermal sensors were located at the mid-level of floor / apartment height (i.e. 1.3 m above the floor level or 1.3 m below the ceiling level) in the middle of the bedroom, middle of living room, in the center of each stairwell inside the public hallway.

As heat and smoke tends to move upwards, it is obvious that the temperatures would be higher towards the ceiling level and lower towards the floor level. Monitoring the temperatures at mid-level of floor height would help to check whether the fire conditions are safer for crawling firefighters.

In such complex structures with multiple stairwells, the location of fire with respect to attack and ventilating stairwell plays very important role. Therefore, several fire scenes were simulated assuming fire was ignited in central or rightmost or leftmost apartment.

As there are several possibilities for attacking and venting these fires, the simulations were repeated for all relevant cases.

In all simulations, fire behavior was similar to the temperature curves plotted in our previous publications. Similar to modern fire behavior curve, fire slowly begins to grow after ignition.

After the windows failure, with more availability of the air, fire grows rapidly, spreads into public hallway, and temperature at all locations increased rapidly.

The fuel in the apartment quickly becomes ventilation-limited and temperature in the apartment begins to drop slightly. As soon as firefighter open the stairwell doors, with the additional air entering the fire apartment, the temperature inside the apartment increased again.

In all cases, as expected, the deployment of PPV fan mitigated the spread of smoke and heat into the attack stairwell.

The combustion products which were pushed back by PPV at attack stairwell were vented through the ventilation stairwell or driven back into the fire apartment and escaped through the broken window. Therefore, the temperature at the ventilation stairwell and inside the apartment continued to increase.

Whereas, the temperatures at the attack stairwell dropped and created safer environment for rescue firefighters. For fire in each apartment, the effectiveness of PPV varied depending on choice of attack stairwell and ventilation stairwell which has

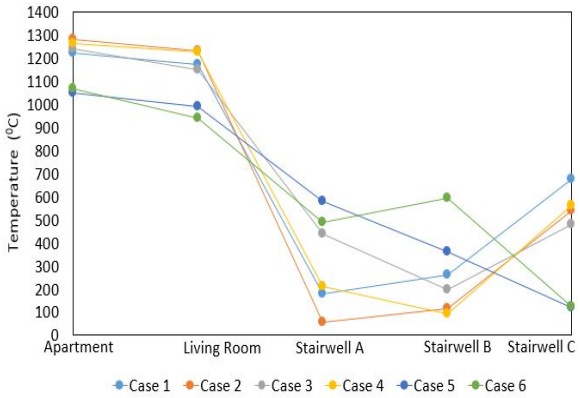


Fig. 3: Temperature distribution for leftmost apartment

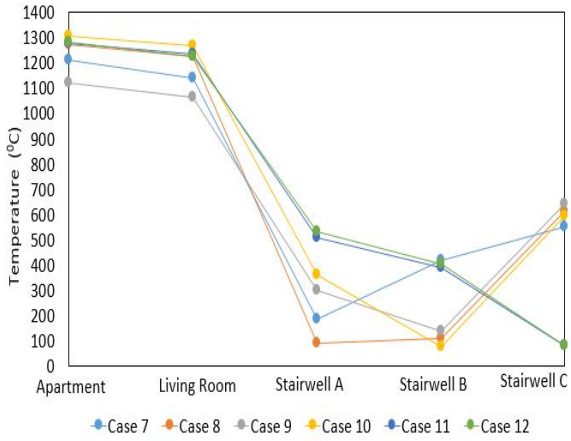


Fig. 4: Temperature distribution for central apartment

been shown in Fig. 3-5. At the end of simulation (70 seconds after opening the door of attack stairwell), the recorded temperatures were stabilized to some extent as the constant PPV flow continued to interact with the continuous generation of heat and smoke. Therefore, the final temperature at various locations inside the structure are used to compare the efficacies of possible PPV tactics. These cases are listed in Table 4.

As the main purpose of PPV is to assist firefighters in making an effective entry on the fire floor, the efficacy of PPV is primarily evaluated based on the thermal conditions at the attack stairwell. In all cases, it was found that PPV tactic is more effective if the attack stairwell is closer to the fire apartment and ventilation stairwell is farther from the attack stairwell. For example, in case of rightmost location, firefighters would experience safer environment if they choose stairwell C (which is closer to the fire location) as attack stairwell and vent the heat and smoke inside public hallway through stairwell A or B (which are farther from attack stairwell). Whereas, for the leftmost location, firefighters should choose stairwell A or B as attack stairwell

Fire Apartment	Attack Stairwell	Ventilation Stairwell	Case Number
Leftmost Apartment	Stairwell A	Stairwell B	1
		Stairwell C	2
	Stairwell B	Stairwell A	3
		Stairwell C	4
	Stairwell C	Stairwell A	5
		Stairwell B	6
Central Apartment	Stairwell A	Stairwell B	7
		Stairwell C	8
	Stairwell B	Stairwell A	9
		Stairwell C	10
	Stairwell C	Stairwell A	11
		Stairwell B	12
Rightmost Apartment	Stairwell A	Stairwell B	13
		Stairwell C	14
	Stairwell B	Stairwell A	15
		Stairwell C	16
	Stairwell C	Stairwell A	17
		Stairwell B	18

Table 4. Various scenarios based on choice of attack and ventilation stairwell

and vent the heat and smoke through stairwell C. In case of fire in central location, firefighters can choose any of the stairwells as they are at almost same distance from fire location but the heat and smoke should be vented through the farthest stairwell from the attack stairwell.

Generally, in case of scissor type stairwell, firefighters should never use stairwell A as attack stairwell and stairwell B as ventilation stairwell or vice-versa. In this scenario, the positive pressure created by the fans mitigate the venting flow of combustion products and the heat gets trapped in the public hallway.

For example, in case of fire in leftmost location, if firefighters plan to attack through stairwell A and vent the heat from stairwell B, the positive pressure pushes the heat to a dead end as stairwell C is closed. Please note that too many vents are not recommended as it decreases the level of positive pressure and the intensity of PPV tactic.

When a stairwell farther from fire location is chosen as attack stairwell, the positive pressure zone was not able to push the hot gases back into the fire apartment as it has to travel long public hallway. For example, in case of fire in rightmost apartment, the case 17 and 18 showed lower temperatures at the attack stairwell and higher temperatures inside the apartment which indicates that PPV was successful in pushing the heat away from firefighters. One may argue that PPV is dangerous for the occupants trapped inside the fire apartment.

Although this may be a valid argument, the temperatures inside the apartment for fire without PPV scenario are approximately of the same order and probability of survival at such high temperatures would be lower and similar in both scenarios. At least PPV could maintain tenable conditions at the attack stairwell and create vantage point for firefighters who can rescue the trapped occupant.

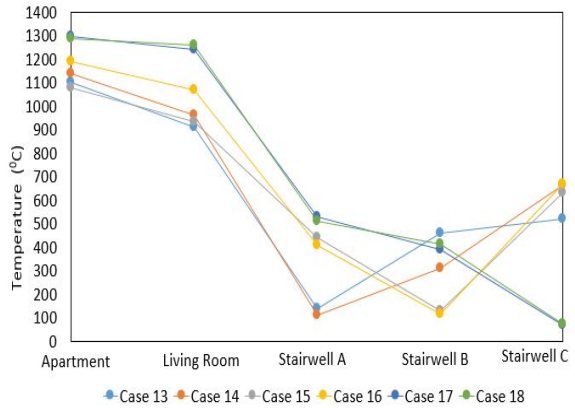


Fig. 5: Temperature distribution for rightmost apartment

CONCLUSION

Several possible fire scenarios with PPV were simulated for a large high-rise structure with multiple stairwells that provide multiple options for attacking and venting points. It was found that PPV is more effective if firefighter choose to attack from the stairwell which is closer to the fire apartment and vent through the stairwell farther from the attack stairwell. Scissor type stairwells should not be used for attacking and venting at the same time. These findings can help fire service to establish guidelines for fighting fires in similar structures and improve the safety of firefighters.

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REFERENCES

[1] D. Madrzykowski, S. Kerber, S. Kumar, and P. Panindre, "Wind, Fire and High-Rises," Magazine of American Society of Mechanical Engineering, vol. 132, no. 7, pp. 22-27, July 2010.

[2] P. Panindre, S. Kumar, A. Narendranath, V. Manjunath, V. Chintaluri, and V. Prajapati, "Optimization of Positive Pressure Ventilation for Wind Driven Fires," Proceedings of the International Mechanical Engineering Congress & Exposition, vol. 4, pp. 1561-1569, November 2011.

[3] P. Panindre, S. Kumar, A. Narendranath, V. Manjunath, and J. Ceriello, "Technique to Improve Performance of Positive Pressure Ventilation Tactic in High Rise Fires," Proceedings of the International Mechanical Engineering Congress & Exposition, vol. 4, pp. 1571-1579, November 2011.

[4] J. Dalton, P. Panindre, E. Smith, R. Wener, and S. Kumar, "ALIVE Training Tool Is a Game Changer," FireRescue Magazine, vol. 31, no. 8, pp. 36-41, July 2013.

[5] NYU Fire Research Group, http://engineering.nyu.edu/fire.

[6] T. Lueck, Fire Officials Tackle Challenges of High-Rise Blazes. New York Times, 2008. Available at: http://www.nytimes.com/2008/02/25/nyregion/25fan.html?_r=0

[7] D. Madrzykowski, and S. Kerber, "Fire Fighting Tactics under Wind Driven Conditions: 7- Story Building Experiments," National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, Maryland, Technical Note 1629, 2009.

[8] S. Kerber, and D. Madrzykowski, "Evaluating Positive Pressure Ventilation in Large Structures: High-Rise Fire Experiments," National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, Maryland, NISTIR 7468, 2007.

[9] S. Kerber, D. Madrzykowski, and D. Stroup, "Evaluating Positive Pressure Ventilation in Large Structures: High-Rise Pressure Experiments," National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, Maryland, NISTIR 7412, 2007.

[10] Tempest Technologies, Tempest Belt-Drive Blowers – Specification Sheet. Available at: http://www.tempest.us.com/blowers/beltd.cfm

[11] Pace Scientific, P300-1-inch-D Pressure Sensors & Data Logger, http://www.pace-sci.com/low-pressure.htm

[12] K. McGrattan, G. Forney, J. Floyd, and S. Hostikka, "Fire Dynamics Simulator (Version 5) - User's Guide," NIST Special Publication 1019-5, 2010.

[13] K. McGrattan, S. Hostikka, J. Floyd, H. Baum, R. Rehm, W. Mell, and W. McDermott, "Fire Dynamics Simulator (Version 5) - Technical Reference Guide," NIST Special Publication 1018-5, 2010.

[14] S. Kerber, and W. D. Walton, "Characterizing positive pressure ventilation using computational fluid dynamics," National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, Maryland, NISTIR 7065, 2003.

[15] K. B. McGrattan, A. Hamins, and D. W. Stroup, "Sprinkler, Smoke and Heat Vent, Draft Curtain Interaction: Large Scale Experiments and Model Development," International Fire Sprinkler-Smoke and Heat Vent-Draft Curtain Fire Test Project, 1998.

[16] K. B. McGrattan, H. Baum, R. G Rehm, "Large eddy simulations of smoke movement," Fire Safety Journal, vol. 30, no. 2, pp. 161-178, 1998.

[17] D. Madrzykowski, and R. L. Vettori, "Simulation of the Dynamics of the Fire at 3146 Cherry Road NE, Washington DC, May 30, 1999," US Department of Commerce, Technology Administration, National Institute of Standards and Technology, 2000.

[18] J. Hietaniemi, J. Mangs, and T. Hakkarainen, "Burning of Electrical Household Appliances: An Experimental Study," Technical Research Center of Finland, VTT – Research Note 2084, Finland, 2001.

[19] V. Babrauskas, J. Harris, et. al., "Fire hazard comparison of fire-retarded and non-fire-retarded products," U.S. Department of Commerce, National Bureau of Standards Special Publication 749, 2001.

[20] C. Weinschenk, C. M. Beal, and O. A. Ezekoye, "Modeling fan-driven flows for firefighting tactics using simple analytical models and CFD," Journal of Fire Protection Engineering, vol. 21, no. 2, pp. 85-114, 2011.

[21] C. M. Beal, M. Fakhreddine, and O. A. Ezekoye, "Effects of leakage in simulations of positive pressure ventilation," Fire technology, vol. 45, no. 3, pp. 257-286, 2009.

D. Madrzykowski, "Modern Fire Dynamics," National Institute of Standards and Technology (NIST), Building and Fire Research Laboratory, Gaithersburg, Maryland, 2013. Available at: http://www.nist.gov/fire/fire_behavior.cfm.

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