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NUMERICAL STUDY ON THE INTERACTION OF SPRINKLERS AND HEAT VENTS

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Abstract

Currently, there are available several models to design and evaluate sprinklers and heat vents independently. However, models that study the interaction between these two components are scarce and are not sufficiently developed. The following work first presents a literature review of experiments and models developed to study this interaction. Next, a CFD[1] model is developed based on the large test room from the Swedish National Testing and Research Institute reported by Ingason and Olsson (1992) . In this model, the effect of sprinkler location and water flow on heat vents is studied. A second CFD model based on the report of the National Institute of Standards and Technology (NIST), *Sprinkler, Smoke and Heat Vent, Draft Curtain Interaction* (1998) is also developed to study the effect of vents on sprinkler activation times. A discussion of the experimental results and validation of the two models is presented to then show the main conclusions found during this work.

Resumen

En la actualidad existen varios modelos para diseñar y evaluar independientemente sistemas de rociadores y extractores de calor. Sin embargo, no existen modelos completamente desarrollados que estudien la interacción entre estos dos sistemas de protección. El siguiente trabajo presenta una revisión bibliográfica sobre experimentos y modelos disponibles en la actualidad. Posteriormente, un modelo basado en DFC[2] es desarrollado con base a los experimentos reportados por Ingason y Olson (1992). En este modelo se ha estudiado la influencia que tiene la ubicación y el flujo de agua de los rociadores sobre los extractores de calor. Un segundo modelo es desarrollado con base a los experimentos a gran escala presentados por el Instituto Nacional de Estándares y Tecnología (NIST por sus siglas en inglés). En este modelo, se ha estudiado el efecto que tienen los extractores de calor sobre el tiempo de activación de los rociadores. Este trabajo finaliza con una discusión sobre los resultados de los experimentos y los modelos para luego, presentar las principales conclusiones sobre ésta interacción.

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[1] Computational Fluid Dynamics

[2] Dinámica de Fluidos Computacional

Declaration

This thesis is submitted in partial fulfillment of the requirements for the degree of The International Master of Science in Fire Safety Engineering (IMFSE). This thesis has never been submitted for any degree or examination to any other University/programme. The author(s) declare(s) that this thesis is original work except where stated. This declaration constitutes an assertion that full and accurate references and citations have been included for all material, directly included and indirectly contributing to the thesis. The author(s) gives (give) permission to make this master thesis available for consultation and to copy parts of this master thesis for personal use. In the case of any other use, the limitations of the copyright have to be respected, in particular with regard to the obligation to state expressly the source when quoting results from this master thesis. The thesis supervisor must be informed when data or results are used.

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Read and approved

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Chapter 1

Introduction

In despite of the availability of models to design and evaluate sprinklers and vents independently, there is no a straightforward model to describe the combined effect of these two components working together.

While sprinklers are used to suppress or control a fire, vents are used to extract heat and smoke from a room. However, when used together, the interaction of both can in some cases enhance or decrease the functionality of each component.

For more than 60 years, there has been a debate of positive and negative claims of this interaction based on conclusions and opinions of experiments and real fires, where sprinklers and vents were present. The first significant research was conducted one year after the Livonia automobile factory fire (1953) where manually opening skylights helped firefighters to attack the fire. In the early 1970's, heat vents were already considered as a protection system by UL and FM.

Beyler and Cooper [1] present an overview of this claims based on conclusions and analysis of several studies, these claims are present below to have a better understanding of the problem:

Positive claims

- *Smoke and heat vents increase visibility:* One of the main functions of heat vents is the extraction of smoke, which directly increases visibility.
- *Heat vents reduce temperature and hazardous gas concentrations:* The extraction of hot gases reduce temperature. The replacement of toxic gases for cool and clean air helps evacuation and action of firefighters.
- *Heat vents contain damage to the curtained space:* Smoke and heat are trapped within the curtained area and are vented to the outside (when draft curtains are used).
- *Heat vents assist the fire department to identify the location of the fire within the facility and reduce the need for hazardous manual roof venting:* This is positive only when smoke is trapped in a curtained area. Vents would point out the location of the fire from the outside. If smoke is not trapped, it would flow randomly all over the place and location of the fire wild not be possible to identify. A second benefit is to avoid to manually cut holes in the ceiling. This is a common practice of firefighters to enhance ventilation in a room.
- *Heat vents provide protection even if the sprinklers do not work:* Even though sprinklers are very effective, vents might work as a backup.

- *Heat vents prevent an excessive number of sprinklers from operating:* By containing the smoke in a curtained area, only sprinklers in the fire area are activated.

Negative claims

- *Heat vents will cause enhanced burning rates:* For an effective extraction of smoke from the vents, air from lower levels should be supplied. This air is supposed to maintain the burning rate of a fire.
- *Heat vents will delay sprinkler activation:* Venting of gases and smoke will result in lower gas temperatures at the ceiling, which will delay activation of sprinklers.
- *Heat vents increase the number of activated sprinklers:* This is explained in two ways. The first one is that the delay of the first sprinkler activation will cause the increase of the fire, consequently, this will cause more sprinkler activations during fire control. The other explanation is that heat within the curtained area will increase the temperature at remote locations within the curtained area.
- *Heat vetns are not cost effective:* The cost-benefit relation of vents is not convenient.

As mentioned before, even though these claims are based on experimental studies, its validity depend drastically on the experiment set-up. Location of the fire, number and size of the vents, geometry of the room, specification of sprinklers, among many others, are examples of parameters that might affect the interaction.

Due to the high cost of large scale experiments, recent studies use a numerical approach. The development of more accurate models and the implementation of Computational Fluid Dynamic software (CFD) have improved the efficacy of this type of analysis. However, validation experiments and numerical studies are still scarce.

This thesis starts with a literature review of experiments and numerical models mainly focus on the interaction between sprinklers and natural vents. Two experiments of this review have been selected to develop numerical simulations. A methodology for the model set-up is presented to then show the results and a discussion. Finally conclusions of the main findings are presented.

1.1 Objectives

The objective of this thesis is to investigate the interaction of sprinklers and natural vents. In order to do this, a reference test case is defined based on actual experiments for validation purposes. Two separate simulations of a fire with and without vents will be first performed in order to set a benchmark of common measurable parameters (temperature, velocity, smoke layer, etc,). Then, sprinklers will be added to both fire scenarios at different locations and water flow rates to study their effect at different conditions.

Simulation with a large domain that involves a full array of sprinklers and a single vent, will be also performed and compared with a real case scenario.

Chapter 2

Literature Review

This section recapitulates several studies on the interaction of sprinklers and natural vents. The first part divides tests with sprinklers and vent arrays and tests with a single sprinkler and a single vent. Tests including arrays, focus on the number and time of sprinkler activation and in some cases obscuration. Tests with single components focus on smoke extraction efficiency, temperature reductions and drag force from sprinklers. The second part describes numerical models developed to study this interaction and it is also divided in two parts, zone and field models. While zone models usually offer an overview of the smoke layer properties and do not offer information of the local effects of the components, field models offer a more detailed solution. However, validation of the interaction is still scarce.

2.1 Experiments

Tests to investigate the interaction between sprinklers and natural vents have been reported since the middle decade of 1950. Most of the tests reported before the beginning of this century have been relatively large scale tests with factory-like building features; mainly due to the fact that it is likely to find these two protection systems working together on this kind of buildings. Since the 90's there have been experiments characterized for the presence of a single sprinkler and a single vent and rooms that do not exceed 70 m^2.

The following sections explain all these tests and present references were more detailed information can be found. It is important to note that conclusions of each test are extracted from the same report and do not represent interpretations of other authors.

2.1.1 Large Scale Experiments

Beyler [1] presents an overview of tests performed during the past 65 years; some of them have been the base for a legislation that is still valid. The table below shows a brief summary of the tests explaining its main features and findings. Further information can be found in [1]. A more complete explanation of the Large-Scale experiment ***UL's 1998 Sprinkler, Vent, Draft Curtain Fire Test*** will be also presented since this test is the basis of a Large-Scale simulation for this project.

Table 2.1: Large Scale Tests [1].

Test	**Main Features**	**Remarks**
(1955) Armour Research Foundation Reduced-Scale Vent Tests	Room Size: 1/8 and 1/16 sclae models of factory-like building. HRR:13.6 MW. Sprinklers present with water density of 10.2 Lpm/m2.	It was found that a vent area to floor of 1:30 was suitable. Sprinklers removed about 35 of the energy released by the fire. The results provided the basis for NFPA 204.
(1956) FMRC's Test on Vents, Curtains, and Sprinklers	Room Size: 36.6 x 18.3 m, HRR: 10 MW. Sprinklers and curtains used. Test with and without sprinklers.	Vents reduced significantly temperature in unsprinklered tests, however in sprinklered test its roll was rather modest. Vents did have a positive impact on visibility in sprinklered test.
(1958) FRS Fire Vent Research	n/a	n/a
(1964) Tests on Effects of Vents on Sprinklered Fires	Room Size: 18 x 18 x 5 m, Vent area to floor 1:100. Fire: 1.8 high crib. Test with and without vents.	Vents decreased the number of operating sprinklers, decreased total water demand and increased roof temperatures.
(1966) Portsmouth Fire Tests	Room Size: 18 x 11 x 8 m. Test with and without vents.	Temperature increased over three times in the experiment without vents. In the vented test low temperature and smoke levels allow firefighters extinguish the fire.
(1970) FMRC's Model Study of Venting Performance in Sprinklered Fires	Room Size: 6 x 4.8 m^2 Fire: Heptane pools and thick triwall cardboard arrays of height of 0.5 m with no aisles. Vents, draft curtains and sprinklers present.	For heptane pool fires vents and curtains reduced water demand and improved visibility. In cardboard tests there was no difference in the number of activated sprinklers with and without vents. Oxygen concentration for unvented test was about 18 while for vented test 20.
(1980) IITRI's Full-Scale Vent/Sprinkler Research Tests	Room Size: 23 x 7.6 x 5.2 m. Fire: Propane burner of 3.4 MW and wood pallets. Vents, sprinklers and curtains present	For propane fire, roof vents did not affect either sprinkler activation times nor number of activated sprinklers. Vents did improve visibility. For the wood fire the average number of sprinklers activated was the same for vented and unvented tests with a standard deviation of 6% and 3% respectively.
(1989) Ghent Test [8]	Room Size: 50 x 18 x 10 m. Fire: Hexane pool fire, one steady of 5.4 MW and a growing fire with peak value of 10 MW.	Vents reduced temperature in the upper portion of the curtained area. Increasing the number of vents reduced the number of sprinklers activated. In experiments with no vents, sprinklers provided water in areas where no fire was present.

2.1.1.1 (1998) UL's Sprinkler, Vent, Draft, Curtain Fire Test [11]

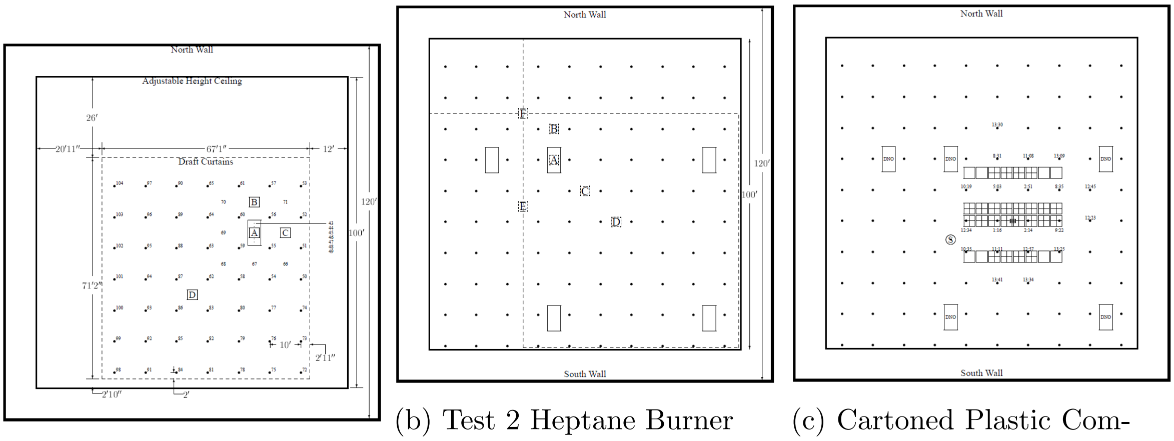
Three experiments were done at the Large Scale Test Facility at Underwriters Laboratories (UL) in Northbrook, Illinois. All experiments used the same room configuration, only vents, fire source and draft curtains were changed of location depending on the test. The following paragraphs will describe first, the common features of the three experiments and then explain their main differences to then present the main conclusions.

The test facility has dimensions 37 m x 37 m and is equipped with an adjustable ceiling of 30.5 x 30.5 m; the height of the ceiling can be adjustable up to a maximum of 14.6 m but for the tests it was raised to a height of 7.6 m. The ceiling was constructed of UL fire rated Armstrong Ceramaguard ceiling tiles with specific heat of 753 J/kg·K, thermal diffusivity of 2.6 x $10^{-}7$ m^2/s, conductivity 0.00611 W/m·K and density of 313 kg/m^3.

Forty-nine Central ELO-231 (Extra Large Orifice) upright sprinklers were installed on a 3 x 3 m spacing basis. The reference actuation temperature is reported to be 74 °C, RTI (Response Time Index) of 148 $(m \cdot s)^{1/2}$ and C factor of 0.7 $(m/s)^{1/2}$. The sprinkler deflector and the thermal element were located 8 and 11 cm respectively.

Vents' dimensions were 1.2 x 2.4 m and they were about 3.0 m above the ceiling and were designed to open manually or automatically. In cases where manual operation was performed, opening times were chosen so that the vent would be either open about 25 s prior or after first sprinkler activation. When operated automatically, it has a fuse with a calculated RTI between 167 and 180 $(m \cdot s)^{1/2}$.

Instrumentation for the test consisted of thermocouples, gas analysis equipment, and pressure transducers. Temperature measurements were recorded at 104 locations, and were intended to measure temperatures near the ceiling, ceiling jet and temperatures near the vent. Oxygen, carbon dioxide and carbon monoxide sampling probes were placed at ground level and at the vent. Differential pressures were measured across the vent and were placed at the center of it, 0.15 m above the top of the vent and 0.15 m below the ceiling. Figure 2.1 shows the main features of the three experimental layouts.



(a) Test 1 Heptane Burner

(b) Test 2 Heptane Burner with draft curtains.

(c) Cartoned Plastic Commodity Fire Test.

Figure 2.1: UL's tests. Sprinklers are solid circles, boxed letters burner locations, rectangles are vents and dashed lines draft curtains.

For tests 1 and 2 a heptane burner of 1 x 1 m was used at different locations (see Figure 2.1a and 2.1b) 0.6 m above the floor. The burner followed a αt^2 curve for the HRR (Heat Release Rate) intended to approximate the estimated growth rate, α, of cartoned plastic commodities tested by Factory Mutual. For the first test, the fire grows until first sprinkler activation or when a specified fire size was reached and then was maintained at that level where steady state conditions were reached. For the second test, a fire of 10 MW was reached in 75 s following an αt^2 curve, after that time the HRR was maintained constant.

For the third test (Cartoned Plastic Commodity Test) the fuel package is a standard test commodity defined by Factory Mutual as a Cartoned Group A Unexpanded Plastic. It consists of polystyrene cups packaged in compartmented, single-wall, corrugated paper cartons, eight of these packages comprise a pallet load. The pallet loads were stored in racks of 6 m and for this test the ceiling height was 8 m. Figure 2.1c shows the array used on one of the several locations implemented and Table 2.2 shows a summary of the tests.

From the results obtained on each test some general conclusion were drawn:

- There is no a significant effect of the number of activated sprinklers, activation time or near-ceiling gas temperatures when vents are opened. Only when the fire was located beneath a vent, there was a longer sprinkler time activation, especially in the first ring of sprinklers surrounding the fire, the earlier the vent opening, the more noticeable the effect.

- Draft curtains increased the number of sprinkler activations and according to the report, the reason for this is that draft curtains lead to an increase on near gas ceiling temperatures, this due to the fact that smoke is accumulated within the curtain region, this makes the smoke layer thicker, which insulate the region close to sprinkler.

Table 2.2: UL Tests.

Test ID	**Fuel**	**HRR**	**Remarks**
Heptane Spray Burner test I	Heptane	3.7 - 6 MW	Fire grow until first sprinkler activation. $\alpha = 1.7$ kW/s^2
Heptane Spray Burner test II	Heptane	10 MW	Fire grow following an αt^2 curve. After 75 s, fire was constant.
Cartoned Plastic Commodity Fire Test	Cartoned Plastic	370 kW/m^2	The total HRR varied depending on how many boxes burnt.

- Also, the thicker the layer, less air entrainment from the smoke plume is allowed to enter, increasing temperature.

- For the cartoned tests, in some cases draft curtains contained smoke in certain regions, making sprinklers outside those regions to not activate, this increased the fire spread over the hole sample due to the fact that commodities were not wet.

- In many of the tests, vents with fusible links did not open even when critical temperatures were reached for several minutes. Two possible explanations for this situation arise; the first one is that the link was cooled by water from sprinklers; second one is that the sprinkler spray cooled the rinsing smoke plume enough to prevent the activation of the vent.

2.1.2 Single Sprinkler-vent Experiments

Few experiments have been reported on the last decade regarding interaction of sprinklers and natural vents; perhaps the most relevant one is the test performed by Ingason and Olsson [9] where two different configurations of roof vents are studied against different sprinkler locations. Other experiments only focus on a single configuration of sprinklers and vents. This section summarizes the experiments giving an explanation of the test, parameters measured and conclusions drawn. It should be noted that a wider explanation for [9] will be given since it is the basis for the scenarios simulated in this project.

2.1.2.1 Interaction between Sprinklers and Fire Vents [9]

These series of experiments were carried out at the Swedish National Testing and Research Institute in 1992 and are divided in four parts as shown in the table below:

Table 2.3: Test series parameters [9].

Test series	**Fire growth rate**	**Fire vent**	**Comments**
Part One	Fast, Medium, Slow, Constant effect 1.2 MW	No vent, Vent eccentric 3 m from center of the test room, Vent above fire source	Three tests were conducted for fast fire growth, two for medium and one for slow.
Part Two	Constant effect 1.5 MW	No vents	One sprinkler located at center of the ceiling. Fire source eccentric 6 m from center of the room.
Part Three	Constant effect 1.5 MW	Vents in the center of room and eccentric 3 m	Sprinkler location varied in relation to the vents.
Part Four	Medium, Constant effects 1.2 MW and 1.5 Mw	Vents in center of room and eccentric 3 m away	Beams mounted in the ceiling.

As it can be inferred from Table 2.3, the first part is intended to compare different vent locations. The second part is intended to investigate the influence of water spray. Part three investigates the effects of water spray on the outflow of hot gases through a fire vent by varying the location of the sprinkler. Finally, part four investigates the influence of beam constructions located in the ceiling on the velocity and temperature fields. As part of the thesis, special attention will be paid to parts two and three, since validation of the simulations will be according to these tests.

Room Characteristics: The internal dimension of the room was 7.5 m x 15 m x 6 m high and it was inside a test hall consisted of an insulated steel construction with dimensions 18 x 22.3 x 20 m high. Inlet air for the test was provided from the floor level and the air flow was uniformly distributed, outlet air was extracted at the top of the hall, as shown in Figure 2.2.

Ceiling was made of 9.5 mm Navilite N boards mounted on a T-profile frame system. The large side walls were made of two different materials; the upper part of the walls (2.4 mm) consisted of 9.5 mm Navilite N boards and the lower part (3.6 m) consisted of 13 mm gypsum boards. Table 2.4 shows the properties of the Navilite board reported on [9]. For some tests, both ends of the room were fully open. In the experiments where the fire source was at one end of the room, a wall was used to cover half of the opening from the top.

Table 2.4: Properties Navilite board

Property	**Value**
Thermal conductivity	0.12 W/mC
Density	700 - 780 kg/m^3
Specific heat	800 kJ/kg

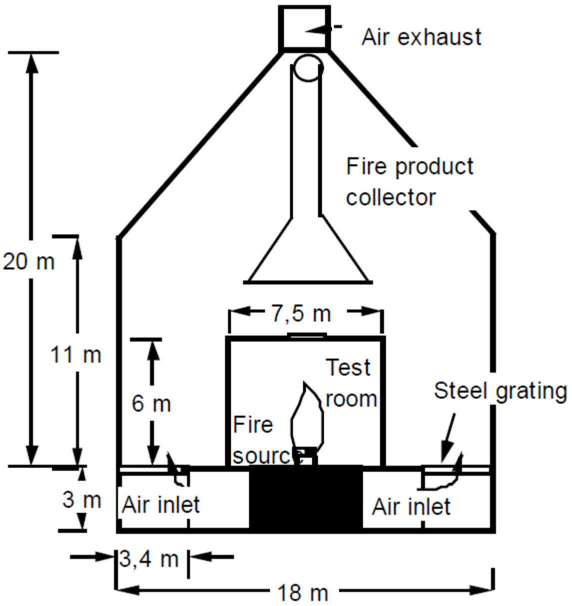
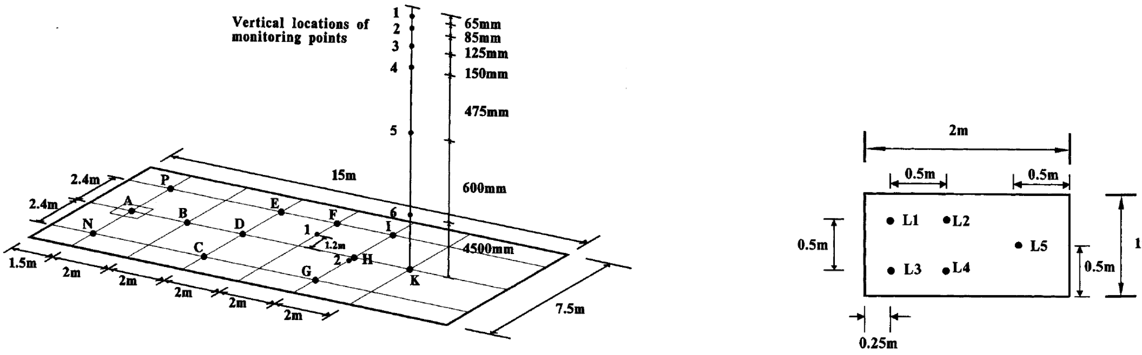


Figure 2.2: Test room and test building [9].

Instrumentation: Thermocouple trees were placed at different locations in the room upstream and downstream the vent and sprinklers. Pressure probes were placed at certain locations for velocity measurements. When a vent was present, thermocouples and a pressure probe were placed 20 mm above the vent on a steel frame. Figure 2.3 shows dimensions, position and height of the devices used.



(a) Location of trees at the room.

(b) Instrumentation at the vent.

Figure 2.3: Location of devices [2].

Fire source: Propane gas burner with dimensions 1 x 1 m. The bottom of the burner was 25 cm above the floor with steel sheets of 20 cm at the surroundings of it. The HRR of the burner was controlled manually by rotating valves.

Two locations of the fire source were used, one at the center of the room and other 1.5 m from one of the ends at the centerline of the test room.

The main purpose of these tests was to offer data for validation purposes for numerical models, therefore the author does not include conclusions of the tests.

2.1.2.2 The Effect of Smoke Vents on the Sprinklers in a Small Compartment [16]

The aim of the test was to study the effect of sprinklers and natural vents on small compartments (less than 100 m^2) very common in Taiwan, where available land is limited and small rooms are widely used for offices, department stores and underground business stores. A fire was placed at different locations of a room with two vents. In some tests the vents were open before or after sprinkler activation and they may work with natural or mechanical ventilation with a given rate. The main parameters measured were temperature profiles, sprinkler activation time and smoke temperature after sprinkler activation. The author also performs a FDS[1] simulation for calculating sprinkler activation times. The list below describes the main features of the test.

- Room Size: 12 x 7 x 3 m high.
- 2 vents of 0.6 x 0.6 m each. One vent is on one wall the other on the ceiling. Part of the experiment is done with natural ventilation the other part with mechanical ventilation.
- Instrumentation: 8 thermocouple trees were placed around the center of the room, pressure on the sprinkler system was measured.
- 45 sprinklers were used on the experiment with a water flow of 80 l/min.
- Fire Source: Methanol pool fire with maximum HRR of 167 kW, the source was placed at three different locations, one of them under a sprinkler head.

Main Conclusions: Vents should be open after activation of sprinklers in order to maintain tenability limits. Sprinkler systems did reduce smoke temperatures, for fires located near the walls the temperature may drop 20% to 30% and for fires under a sprinkler up to 50%. For the simulation part, the report shows a good agreement with experiments regarding temperature with deviations lower than 6% however, sprinkler activation times are not that accurate and deviations of 17.5% can be found.

2.1.2.3 Experimental investigation on drag effect of sprinkler spray to adjacent horizontal natural smoke venting [10]

The main purpose of this test was to investigate the drag effect of sprinklers on the efficiency of adjacent smoke venting. Measures of velocity of smoke through vents, smoke layer thickness, temperature and CO_2 concentration were taken under different sprinkler operating pressures. The main features of this test are presented next:

- Room: consist of two cabins, one where the pool fire is located and other where the smoke produced by the burner interacts with a sprinkler and vents. The fire room dimensions are 4 x 2 x 2.5 m high and the sprinkler cabin has the same area but is 4.2 m high. It has 2 m high smoke curtains to guarantee a stable smoke layer.

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[1] FDS is a Computational Fluid Dynamics (CFD) package that will be presented in the next section.

- Sprinklers: A single ZSTP-15 sprinkler was used with a nozzle diameter of 12.7 mm and a flow rate coefficient of 80. The sprinkler is installed at the center of the adjacent cabin on a pendant position.
- Vents: Two types of experiments were conducted, one with a single adjacent vent (0.6 x 0.6 m) to investigate the impact of sprinkler spray and venting, the other with three vents of the same size to investigate the effect of smoke venting area.
- Fuel: Diesel was used as the burning material with two different pool sizes that yield a steady-state HRR of 248 kW and 476 kW.

Conclusions: The velocity of smoke venting decreases with the increase of sprinkler operating pressure. There is a maximum pressure where the vent can evacuate smoke, beyond this pressure, smoke logging may occur. Drag force from sprinklers plays an important role on smoke venting since where smoke logging was identified, temperature of smoke was always higher than ambient temperature, meaning that drag force from sprinklers was higher and opposite than buoyancy. Due to this drag force from sprinklers, CO_2 concentration increased in the cabin.

For multiple vents, the experiment showed that they reduced the average temperature rise of the smoke layer and velocity flow through a vent. For sprinkler pressures where smoke logging was reported, there is no difference between single and multiple vents.

2.2 Numerical Models

Several studies have arisen since the late 1980's after the survey performed by Heselden [5], where he suggests that due to the complexity of the interaction of both systems (sprinklers and vents) and the different opinions among experts around the world, a numerical model might be the most appropriate tool to determine or explore possible factors that might affect the whole system, as well as find areas where both systems might work properly and areas where not. This section presents numerical models that have been the base of "two-zone" software and field models especially focused on the interaction of sprinklers and vents.

2.2.1 Zone Modeling

2.2.1.1 Hinkley's Model

One of the earliest models conceived for studying the interaction of sprinkles and vents was the one done by Hinkley [7]. The aim of this model is to estimate the effects of roof venting on the opening of first sprinklers. For the implementation of this model Hinkley takes into consideration the following points:

- Well known correlations of entrainment into plumes derived by Thomas and Heskestad.
- Rate of flow through vents due to buoyancy.
- A model suggested by Heselden of radial temperature distribution that includes a very simple model for cooling by the sprinkler.

- A model that allows entrainment of hot gases from the smoke layer into the ceiling jet.

The model was validated with the experiments conducted at Ghent [8]. The following conclusion are drawn:

- The model gives a good estimate of radial temperatures on prior sprinkler activation and in areas not affected by sprinklers after activation.
- Vents did not have a local effect on properties of jet ceiling (specific location or size of individual vents did not affect properties of the jet ceiling.)
- Calculated mean velocities agree with measured velocities.
- The depth of the jet ceiling agrees with calculations.
- The model underestimate the effect of venting in reducing the number of sprinklers operating.

It is important to note that the model was next expanded [6] to study the activation time of subsequent sprinklers, also some validation of this updated model is presented on the test conducted at Ghent. This model is also used as a basis for a two zone model software called RADISM [15].

2.2.1.2 Cooper's Model

The model presented by Cooper [3] gives the physical basis and associated mathematical model for estimating the fire environment and the response of sprinkler on fires within curtained areas with fusible, link-actuated ceiling vents. As Cooper stated, the problem addressed in his work is similar to the one addressed in Hinkley's work [6].

The phenomena that have been taken into account in this model are listed next:

- The flow dynamics of the buoyant fire plume.
- Growth of the elevated-temperature smoke layer in the curtained compartment.
- The flow of smoke from the layer to the outside through open ceiling vents.
- The flow of smoke below curtain partitions to building spaces adjacent to the curtained space of fire region.
- Continuation of the fire plume in the upper layer.
- Heat transfer to the ceiling surface and the thermal response of the ceiling as a function of radial distance from the point of plume-ceiling impingement.
- The velocity and temperature distribution of plume-driven near-ceiling flows.
- The response of near-ceiling-distance fusible links as functions of distance below the ceiling and distance from plume-ceiling impingement.

For describing the phenomena the author uses several correlations such as Heskestas fire plume correlation, conservation of mass and energy principles, buoyancy theory, and also assumptions about the flow inside the smoke layer; i.e. the ceiling flow is considered axisymmetric and it spreads radially over all directions, the ceiling jet when it reaches curtains, it turns downward and form a vertical flow which due to buoyant forces will be stopped and will form the smoke layer.

Assumptions and correlations leads to some limitations of the model, especially on dimensions of the room and curtains; for example if L and W are length and width respectively, the model is limited by the ratio L/W between 1 and 2. There are also limitations on the curtains' size and position of the fire, these can be consulted on Cooper's report.

This mathematical model was implemented in the software LAVENT which has been validated with the experiments performed by Ingason [9] comparing velocities, temperatures profiles and ceiling jet thickness. Results [17] showed that LAVENT predicts thinner ceiling jets and temperatures are underestimated giving very low values compared with the experiment. CFD simulations are also compared and the conclusion of the report is that CFD model predicted better the experiment than the tow zone model used by LAVENT.

2.2.1.3 SPLASH

SPLASH is a multi-zone model that describes the interaction of sprinklers sprays with fire gases in corridors and it uses a mathematical model to describe the motion of the water droplets and the heat transfer between the drops and the gas; it was developed at South Bank University in 1988 [18]. The model has been used to study interaction between sprinklers and vents. In one of these studies it was found that a single sprinkler reduced the efficiency of a natural vent by up to 14%, however there is no comparison with experiments. It is important to note that SPLASH cannot model situations where in-flow and out-flow through vents occurs simultaneously, phenomenon present in several experiments. Further information of other experiment validations can be found in [15].

2.2.2 Field Models (CFD)

This section presents reports of field model simulations of the interaction of vents and sprinklers. Some of them are validation of tests presented in sections above.

2.2.2.1 Numerical Modeling for the UL tests

A numerical model developed by the National Institute of Standards and Technology (NIST) called Industrial Fire Simulator (IFS) based on the Large Eddy Simulation technique (LES) has been implemented for validation purposes of the same large scale tests and also to investigate the change of different parameters that could not be studied during the tests. The report explains how the main parameters of the test are modeled, i.e. fire source, sprinkler activation, sprinkler droplet size distribution, sprinkler spray dynamics and extinguishment of the fire.

For the sprinkler time activation, the model predicted the activation of the first four sprinklers surrounding the fire to within about 5 or 10 s. For the next ring of sprinklers the model underpredicted the activation time by 15 to 30 s. The report suggests that this might be due to the uncertainty of the droplet size distribution. A sensitivity analysis was performed on several parameters and the droplet size was found to be the more important. The reason, according to the report, is that heat transfer between the hot gases and the droplet is directly proportional to the surface area of the droplet. As an example, doubling the size of the droplets reduces the number of droplets by a factor of 8 and reduces the heat transferred from the gas by a factor of 4.

Validation for the fire growth of the cartoned plastic commodity was also made. From cone calorimeter and LIFT tests, some combustion properties from the fuel source were found as a basis for validation with the model. The model provided a very good representation of the heat release rate of the fuel for few minutes after ignition. However, this time was enough to study the most important interactions taking place during the experiment. A big difference was found in the ignition times of the sample and the model, the report suggests as an explanation the simplistic combustion model implemented in the simulation.

Another numerical simulation is made to analyze the mass flow through vents since in some actual tests, vents did not open when they were supposed to open. The analysis is based on the expression for mass flow rate through a vent due to buoyancy as shown in equation 2.1,

$$\dot{m} = \frac{CA_v\rho_\infty\sqrt{2gd\Delta TT_\infty}}{T_\infty + \Delta T} \tag{2.1}$$

where C is an orifice coefficient equal to 0.6, A_v is the area of the vent, ρ_∞ is the density of air, g is gravity, d the depth of the layer of hot gases, ΔT is the average temperature rise in the layer, and T_∞ is the ambient temperature. A comparison between this formula (which does not take into account the presence of sprinklers) and models using sprinklers was done to see differences in the mass flow through vents. The numerical model showed that mass flow through vents with the presence of sprinklers was relatively low (for some cases 45% for others 10% lower) compared with the theoretical maximum value given by equation 2.1, because temperature near the ceiling was reduced due to the action of sprinklers. When the HRR of the fire was increased up to 10 MW, mass flow increased due to the increase of temperature of the smoke layer. Simulations removing draft curtains showed that mass flow dropped into a range of 1.5 kg/s to 2.0 kg/s caused by the decrease of the smoke layer depth but it is also attributed to the change in ceiling jet dynamics when the curtain is removed.

Similarly to actual tests, model simulations showed that when the fire is not located directly under a vent, venting had no significant effect on the sprinkler activation times, the number of activated sprinklers and ceiling gas temperatures. When the fire was located under a vent, vent activation and first sprinkler activation occurred about at the same time but activation time for outer ring sprinklers was delayed. The model also showed that when draft curtains were installed, more sprinklers were activated.

2.2.2.2 Simulation of Sprinkler-Hot Layer Interaction Using a Field model [2]

This paper reports the interaction of sprinkler water spray with a smoke layer using the Reynolds-averaged Navier-Stokes equations (RANS) technique. Chow divides the problem in a liquid phase and a gas phase, assuming that the water spray discharged from the sprinkler is taken as water droplets moving under gravity and air drag. The liquid phase of the problem is solved with a Lagrangian approach for describing droplet motion; by calculating positions, velocities and sizes of water droplets using Newton's law of motion and a Rossin-Rammler distribution function. For this part of the problem evaporation was not considered for water droplets. The gas phase problem is a buoyancy-driven flow problem and equations for describing transport of mass, momentum, enthalpy and turbulent parameters are used.

Chow also suggest to calculate a parameter known as the D/B ratio, which accounts for the stability of the smoke layer. This ratio is obtained by summing up the air drag exert on water droplets and the buoyancy of air in every control volume.

For the numerical tests Chow uses part three of the experiments performed by Ingason, where a centric vent is used, a propane burner is placed on one of the ends of the room and sprinklers activated at different locations along the centric length of the room. For this calculation a volumetric fire source of size 2 m^3 was taken to simulate the fire instead of using a propane burner with a combustion reaction, also a non-uniform mesh was implemented with finer mesh sizes near the fire source, sprinkler head and ceiling walls. Figure 2.4 shows the geometry of the test room for this simulation. A HHR of 1 MW and 1.5 MW was used for calculations.

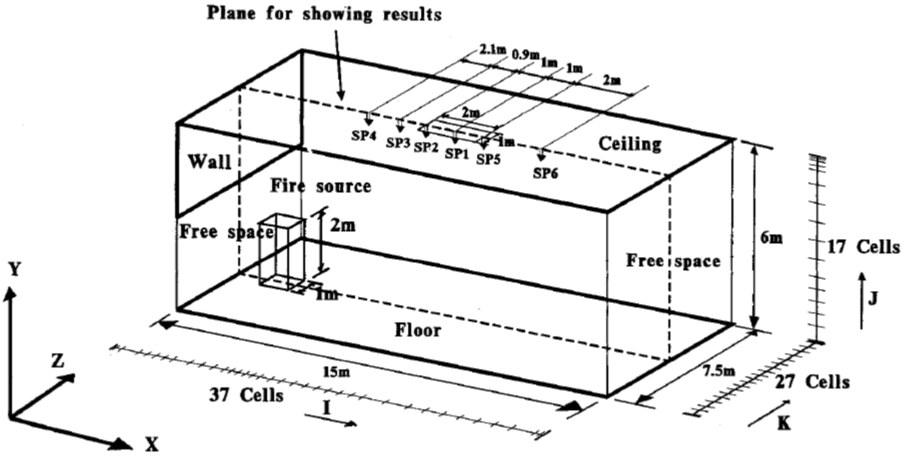


Figure 2. Geometry of the test room.

Figure 2.4: Geometry of the test room [2].

Comparing the numerical results with experiments it was found that there was a fairly good agreement with positions farther from the fire but no to close to the boundary. The former is explained by the use of a non-combustion model and the later by the lack of experimental data for the free boundary conditions. For the D/B ratio as a macroscopic parameter, it was concluded that it was not a good parameter for specifying the stability of the smoke layer, since in all calculations the ratio was below 1, however smoke logging was found in some regions. Deviations at the measure points in the vent are considerably high for the three cases (no sprinkler, 80 l/min and 100 l/min), they vary from 23 % and goes up to 111.1% for velocity measurements.

2.2.2.3 Large Eddy Simulation of Sprinkler Interaction with a Fire Ceiling Jet [14]

Even though this report is not intended to study specifically the interaction between sprinklers and vents, it does study the interaction between the water sprinkler spray and the fire ceiling jet and it uses as a validation reference the experiments done by Ingason [9], it is also important to notice that this is the only LES simulation for these experiments and will be an important benchmark for the work of this project.

For these simulations, vents have not been taken into account and only sprinklers with two sprinkler flow rates (80 and 100 l/min) were implemented. Due to the lack of information about sprinkler specifications, O'grady and Novozhilov [14] have made some estimations showed in Table 2.5. For this study, FDS 4.07 was used as the software for the simulations.

Table 2.5: Sprinkler parameters and estimated sprinkler parameters [14].

Parameter	**80 l/min spray**	**101 l/min spray**
Operating pressure	1.0 bar	1.6 bar
K-factor	80 l/min bar$^{1/2}$	80 l/min bar$^{1/2}$
Distance from ceiling	0.34	0.34
Atomization length	0.2 m	0.2 m
Droplet Volume median diameter	828 μm	709 μm
Droplet initial velocity	5.58 m/s	7.04 m/s
Upper spray angle (from south pole)	115°	115°
Lower spray angle (from the south pole)	65°	65°
Distribution function parameter, σ	0.6	0.6
Distribution function parameter, β	0.693	0.693
Distribution function parameter, γ	2.4	2.4

A grid sensitivity analysis was implemented using 6 different meshes ranging from 20 cm to 7.5 cm. The 7.5 cm mesh was used for temperature and velocity calculations since the analysis showed more accurate values, specially for velocity, which seems to be very sensitive to mesh size. Results at several locations show that for unsuppressed fires, temperature calculations compare favorably especially farther from the fire. For devices closer to the fire, calculated temperature deviate from experimental measurements (10-15%). The report states that this might be due to the limitation of the combustion model and inadequate resolution of the fire region. For velocity values, the simulation predicts the shape of the profile along the height of the room with deviations between 7 -8%.

Besides temperature and velocity calculations, a sensitivity analysis was also performed on different sprinkler parameters. The median droplet size was changed from very fine particles (6 μm) to coarse ones up to 1000 μm. The analysis showed that for median sizes of 600 and 1000 μm, the results are almost identical, and suggest values below 500 μm for better agreement with measurements. The droplet size is based on the Rosin-Rammler distribution (Equation 2.2). Exponent γ was changed with different values, showing that results are not very sensitive to this parameter.

$$f(n) = \begin{cases} \frac{1}{\sqrt{2\pi}} \int_0^D \frac{1}{\sigma D'} exp\left(-\frac{[ln(D'/D_{v,05})]^2}{2\sigma^2}\right) \mathrm{d}D' & D < D_{v,0.5} \\ 1 - exp\left(-0.693\left(\frac{D}{D_{v,0.5}}\right)^{\gamma}\right) & D > D_{v,0.5} \end{cases} \tag{2.2}$$

Sprinkler spray cone was also analyzed comparing three different variations, narrow, standard and wide spray cone; and it concluded that the standard spray cone is the one with more accurate values.

Finally the report compares RANS simulations done by Chow [2]; first noting that the fire used for LES simulations is 1.5 MW and for RANS 1 MW and the sprinkler flow rates for RANS were 60 l/min and 80 l/min. Other differences on the models used are also pointed out; for example, the fact that in Chow model droplets are assumed to be non-evaporating and also a volumetric heat source is used to represent the fire. Other sprinkler parameters are compared as well, such as sprinkler proportionality constant, initial droplet velocity and droplet diameter. Comparison of numerical simulations clearly show that LES calculations are in a better agreement with experiments measurements, showing deviations of the order of 15% maximum.

Chapter 3

Methodology

This project will be divided in two sections; the first one is a simulation of a reference test case with a reduced domain where interaction between a single sprinkler and vent will be studied and compared with experimental data. For the second part, a large scale simulation of a real case scenario will be implemented and data will be compared for verification purposes. The following sections presents the set-up of the different simulations.

3.1 Mathematical Model (FDS)

The software implemented for this simulations is FDS 6.1.1 with OpenMPI 1.6.5. Simulations were carried out on a Dell PE 1950 with 2x quadcore Intel Xeon 2.66GHz and 16GB memory server. This section will show the model and the most important features of the experiment.

3.1.1 Turbulence Modeling

Modeling of turbulence is based on the LES technique. Two different models for the turbulent viscosity, μ_t, are tested. The first one is the default value used in FDS 6.1.1 which is the Deardoff turbulent viscosity [12] and the second one is the Constant coefficient Smagorinsky model [12].

Turbulent viscosity, μ_t, for Deardoff model is given by,

$$\mu_t = \rho C_v \Delta \sqrt{k_{sgs}} \tag{3.1}$$

where $C_v = 0.1$ and the subgrid scale (sgs) kinetic energy is taken from an algebraic relationship based on scale similarity [13].

The Constant coefficient Smagorinsky model is given by,

$$\mu_t = \rho (C_s \Delta)^2 |S| \tag{3.2}$$

where $C_s = 0.2$ and Δ is the filter width. It is important to mention that this model is used in FDS versions 1 through 5. Turbulent diffusivity for both models are obtained using a constant Schmidt and Prandtl number.

3.1.2 Combustion Modeling

The combustion model is the Single-Step, Mixing-Controlled Combustion which considers the reaction of fuel and oxygen as infinitely fast and controlled by mixing. Fuel is considered composed of C, H, O and N. It reacts with oxygen to form H_2O, CO_2, soot and CO. The stoichiometric equation assumed by FDS is of the form,

$$C_xH_yO_zN_v + v_{O_2}O_2 \rightarrow v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_SSoot + v_{N_2}N_2 \tag{3.3}$$

User must specify the Fuel (i.e propane, C_3H_8), the yield of CO and soot, and the volumetric fraction of hydrogen in the soot, X_h. For this thesis, CO is taken as the default value (0) since this product is not relevant for the analysis, and soot is considered to be only carbon, therefore X_h is equal to 0. Further information about the model can be found in [12].

3.1.3 Heat Transfer

The heat conduction for solids is given by a one-dimensional heat conduction equation presented below,

$$\rho_s c_s \frac{\delta T_s}{\delta t} = \frac{\delta}{\delta x}\left(k_s \frac{\delta T_s}{\delta x}\right) + \dot{q}_s'' \tag{3.4}$$

where k_s, ρ_s. and c_s are the component-averaged material conductivity, density and specific heat, respectively. $\dot{q}_s''$ is a source term that consist of chemical reactions and radiative absorption.

The default convection model is given by the following equation,

$$\dot{q}_c'' = h(T_g - T_w); h = max\left[C|T_g - T_W|^{1/3}, \frac{k}{L}Nu\right] \tag{3.5}$$

where C is a empirical coefficient for natural convection (1.52 for a horizontal plate and 1.31 for a vertical plane o cylinder), L is a characterized length related to the size of the physical obstruction, and k is the thermal conductivity of the gas. Nu is the Nusselt number.

Radiation is modeled with a Radiative Transport Equation (RTE) and it is represented by the divergence of the heat flux vector in the energy equation,

$$\dot{q}_r''' = -\nabla \cdot \dot{q}_r''(x) \tag{3.6}$$

The RTE is solved using 100 discrete angles (default value) which are updated over multiple time steps.

3.1.4 Sprinkler Modeling

3.1.4.1 Ingasson Model

The sprinkler in the experiment was a Wormald A CU/P K-80 used at two different flow rates, for this case 80 l/min and 101 l/min. The sprinkler is at pendant position 340 mm from the ceiling. Apart from this specification and some drawings of the approximative area where the droplets hit the ceiling, there is no more information available about sprinkler parameters. O'Grady and Novozhilov [14] suggest a base parameters based on previous research and a sensitivity analysis. These parameters are presented in Table 2.5, and the ones used for this simulations are presented in Table 3.1.

Table 3.1: Sprinkler parameters for simulation.

Parameter	**80 l/min**	**101 l/min**
Operating pressure	1.0 bar	1.6 bar
K-factor	80 l/min bar$^{1/2}$	80 l/min bar$^{1/2}$
Distance from ceiling	0.34	0.34
Atomization length	0.05 m	0.05 m
Droplet Volume median diameter	500 μm	500 μm
Droplet initial velocity	5.58 m/s	7.04 m/s
Upper spray angle (from south pole)	115°	115°
Lower spray angle (from the south pole)	65°	65°
Distribution function parameter, σ	0.47	0.47
Distribution function parameter, β	0.693	0.693
Distribution function parameter, γ	2.4	2.4

The operating pressure, K-factor and distance from ceiling are given from the experiment. For the atomization length, the default value of FDS has been used since according to the sensitivity analysis done by O'Grady and Novozhilov [14], this length has very little influence on the results.

The droplet volume median diameter has been chosen to be 500 μm based on the conclusions from the same report where it shows that a better agreement can be achieved if median diameter is below this value.

The droplet initial velocity is obtained by dividing the area of the orifice of the sprinkler (in this case 1.27 cm) over the flow. The upper spray angle also has been chosen according to the sensitivity analysis done in [14] where a "wide", "standard"and a "narrow"spray were compared. It was found that the standard spray (which is the one with angles 115°and 65°) is the one with better results. The distribution parameters are from the Rosin-Ramler-Lognormal distribution (Equation 2.2).

The parameter γ is set to its default value from FDS ($\gamma = 2.4$) which also shows good agreement with results in the sensitivity analysis, β also is the default value of 0.693, and σ is found with the formula used by FDS [12] to assure a smooth joint between the two distributions and gives a value of 0.47.

3.1.4.2 Large Facility Fire

For these series of tests the sprinklers are reported to be a Central ELO-231 (Extra Large Orifice) uprights. Table 3.2 shows the parameters used for the modeling.

Sprinklers are located 11 cm below the ceiling with an spacing of 3 m between each one.

Table 3.2: Sprinkler parameters for the large facility fire.

Parameter	**Value**
RTI	148 $m^2 s^2$
C-factor	0.7 $(m/s)^2$
Activation Temperature	74° C
K Factor	164.2 l/minbar$^{1/2}$
Operating pressure	1.31 bar
Initial droplet velocity	8.01 m/s
Upper spray angle	80°
Lower spray angle	5°
Median droplet diameter	1 mm
Distribution function parameter, σ	0.47
Distribution function parameter, β	0.693
Distribution function parameter, γ	2.4

Given that activation time is a variable to study, it is important to show how this variable is modeled. The thermal activation of a fusible link of a sprinklers is given by,

$$\frac{dT_l}{dt} = \frac{\sqrt{u}}{RTI}(T_g - T_l) - \frac{C}{RTI}(T_l - T_m) \tag{3.7}$$

where T_l is the link temperature, T_g is the gas temperature in the surroundings of the sprinkler, T_m is the sprinkler temperature, u the gas velocity, C is the conductivity factor and RTI is the response time index. The last two values are given by the sprinkler's manufacturer.

3.1.5 Vent Fusible Link Modeling

Modeling of the fusible link of the vent is very similar to the equation governing the thermal activation time of sprinklers. However, the C-factor is not considered in this case and it is replaced by a bulk RTI, which does not account for conductive losses from the fusible to the surroundings. The change in temperature with respect to time for the link is given by,

$$\frac{dT_l}{dt} = \frac{\sqrt{u}}{RTI_b}(T_g - T_l) \tag{3.8}$$

where T_l is the temperature of the object, and T_g is the temperature of the gas that pass the object with a velocity u, and RTI_b is the bulk RTI mentioned above which for this case has a value of 175 $(m \cdot s)^{1/2}$.

3.2 Reference Test: Experimental set-up and Numerical Model

For the selection of a reference test case, a literature review has been done in the section above and the experiment done by Ingason [9] has been chosen to be the most appropriate one. This is mainly because of the availability of the data, previous numerical simulations done by other authors [2] [14] and the different locations of vents and sprinklers available in the experiment. Figure 3.1 shows the modeled room with its main features.

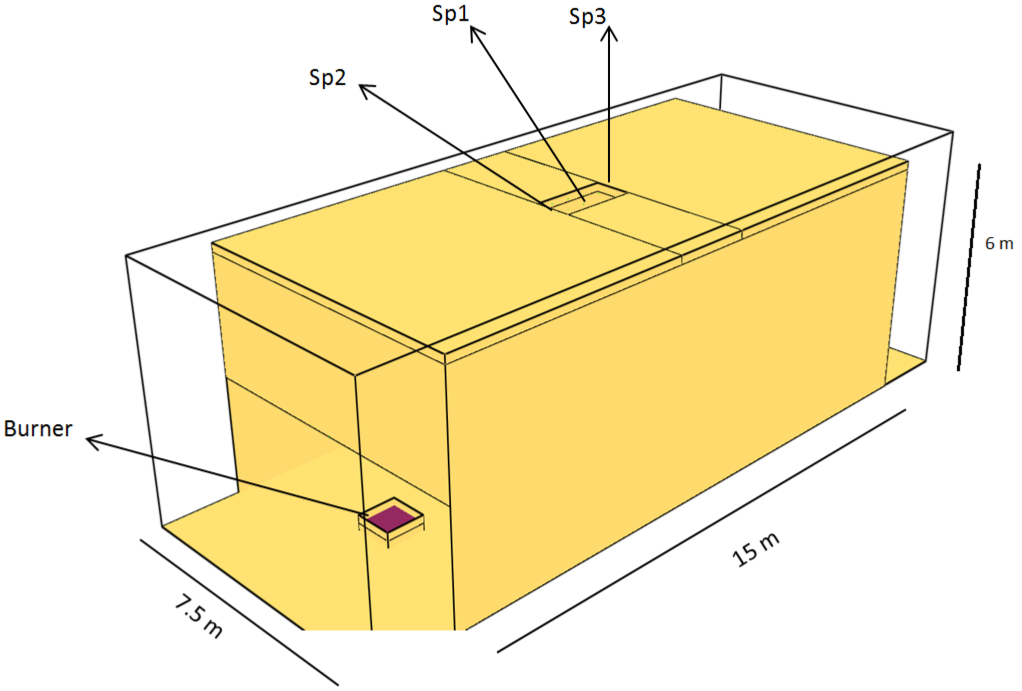


Figure 3.1: Geometry of the reference test room.

3.2.1 Room Geometry

The room has dimensions 15 X 7.5 X 6 m high, 2 meters of additional space has been added at both ends of the room for the intake and outlet of air. One side of the room (the one where the fire is) has half wall starting from ceiling. Properties of the walls are according to the values reported on the experiment, (see Table 2.4) with a thickness of 9.5 mm. For visualization, all the walls are assumed to have no thickness. Ceiling has a thickness of 20 mm (or approximately depending of the grid size), same thickness that is reported for the vents in the experiment. A view of the room can be seen in Figure 3.1.

The vent is located at the center of the room with dimensions 2 x 1 x 0.2 m high. The long side of the vent is parallel to the long side of the room and is aligned to the centerline of it.

3.2.2 Fire Source

The fire source is a propane burner with an area of 1 x 1 m and 25 mm above the floor. The sides of the burner have a steel sheet (for the simulation considered as inert material) of 20 mm high. Properties for the gas were found in [4] and are presented in Table 3.3.

Table 3.3: Propane properties [4].

Properties	**Value**
Soot yield	2.4%
Heat of combustion	46450 Kg/kJ
Radiative Fraction	0.31

The burner is located 1 meter apart from the half wall and it is aligned with the centerline of the room. For this test a constant HRR of 1.5 MW is used.

3.2.3 Measuring Devices

Temperature and velocity devices were placed at several locations of the room according to the configuration given in the experiment. Details of nomenclature and location of each device can be seen in Figure 2.3. Slice devices for temperature and velocity were also implemented in the simulation, these are located at the centerline of the room.

3.2.4 Test Scenarios

Once the cell size is defined and according to Table 3.4; simulations of a propane fire will be carried out for 300 seconds in a room with and without vent (V and NV respectively). After this time, sprinklers will be added at three different locations; one at the center (Sp1), and two at the ends of the vent (Sp2 and Sp3). For each sprinkler two different water flows will be studied (80 and 101 l/min). Table 3.4 shows the tests nomenclature.

Sprinkler 1 (Sp1) is located at the center of the vent, Sprinkler 2 (Sp2) one meter apart from the center of the vent close to the fire source, and Sprinkler 3 (Sp3) is located one meter apart from the vent towards the opposite direction of the fire source. Location are presented in Figure 3.1.

Table 3.4: Reference tests ID.

0 l/min	**80 l/min**	**101 l/min**
NV_NSP_0	NV_SP1_80	NV_SP1_101
	NV_SP2_80	NV_SP2_101
	NV_SP3_80	NV_SP3_101
V_NSP_0	V_SP1_80	V_SP1_101
	V_SP2_80	V_SP2_101
	V_SP3_80	V_SP3_101

The simulation time of each test will be according to the experiment. Table 3.5 shows the tests time line.

Table 3.5: Simulation time line.

Time (s)	0-150	150-300	300-360	360-540	540-600	600-780
Phase	Pre-burn period	Temp. and vel. recorded	Stabilization period	Temp. and vel. recorded	Stabilization period	Temp. and vel. recorded
Sprinkler flow	0 l/min	0 l/min	80 l/min	80 l/min	101 l/min	101 l/min

3.2.5 Grid

Four different grid sizes are used in a sensitivity analysis to establish the best grid resolution. Table 3.6 shows these mesh sizes.

Table 3.6: Reference test cell size

Grid Number	**Cell size (cm)**
1	20
2	12.5
3	10
4	7.5

The test for the sensitivity analysis is the room with no vents and no sprinklers (NV_NSP_0). In order to establish the best grid resolution, comparison of grids with the finer grid will be done calculating the deviation of the results of each measure tree with the following formula:

$$D_T = \frac{|T_{mod} - T_4|}{T_4}; D_U = \frac{|U_{mod} - U_4|}{U_4} \tag{3.9}$$

where T_{mod} is the temperature on the device and T_4 the measured temperature with the finer grid. U_{mod} the velocity on the device and U_4 the finer grid velocity value.

The averaged deviation on each location will be compared with each cell size to determine the sensitivity of results to the grid and establish the most suitable one for the calculations.

3.3 Large Facility Fire: Experimental set-up and Numerical Model

A test from [11] has been selected to investigate the effect of vents on sprinkler activation time. The test is part of the first section of the report called **Heptane Spray Burner Tests, Series I.** Figure 3.2 shows the set-up of the actual test. The solid circles are the sprinklers and the number beside them are thermocouples located near each sprinkler at 10 cm below the ceiling. The dashed line represents a draft curtain, however, for the tests considered in the analysis, draft curtains are not present. The rectangle represents the location of the vent, and capital letters

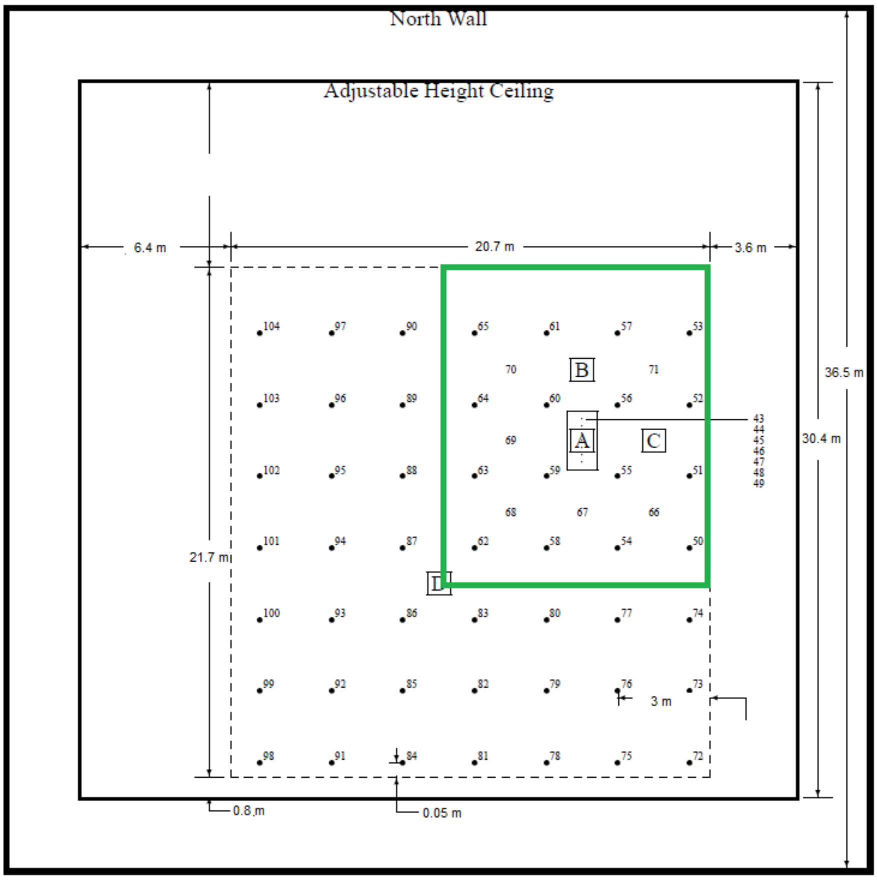


Figure 3.2: Geometry of the Large Facility Fire Test Room. The green area indicates the simulated area.

inside a square are different locations of the burner. For the analysis only burner C will be considered. The green area is the area considered for the simulation.

Figre 3.3 shows the numerical representation of the green area indicated in Figure 3.2.

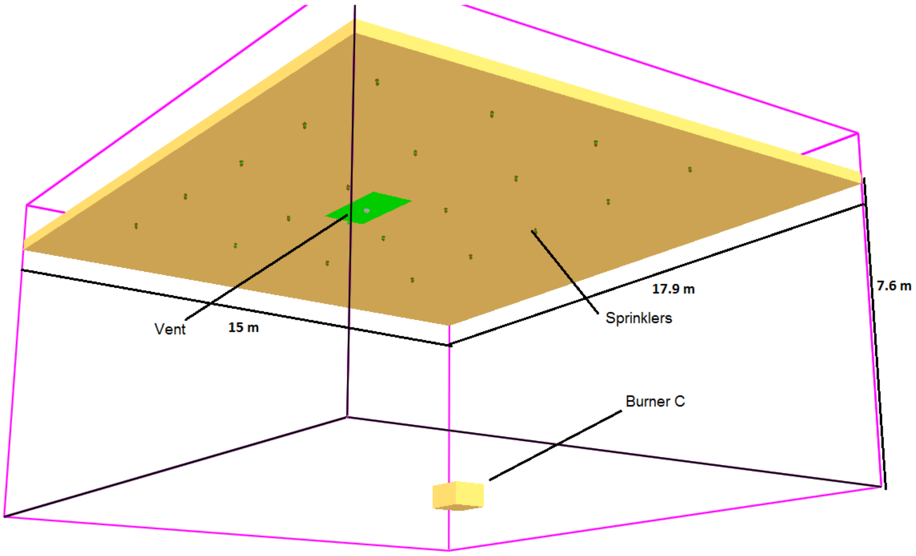


Figure 3.3: Area of simulation.

3.3.1 Room Geometry

The room has dimension 36.5 X 36.5 m and an adjustable ceiling that for the case of this test is set to a height of 7.6 m. The simulated area has dimensions of 15 X 17.9 m, it contains a vent of 1.2 m by 2.4 m in the location shown in Figure 3.2. The ceiling was constructed of UL fire rated Armstrong Ceramaguard ceiling tiles of 0.6 m thick. Properties of the ceiling are presented in Table 3.7.

Table 3.7: Properties of the ceiling material

Properties	**Value**
Specific heat	753 $J/kg \cdot K$
Thermal diffusivity	$2.6 \times 10^{-2} m^2/s$
Conductivity	0.0611 $W/m \cdot K$
Density	313 kg/m^3

3.3.2 Fire Source

The fire source for this case is a heptane burner with an area of 1 x 1 m and 0.6 m above the floor. The location of the burner is represented with the letter C in Figure 3.2. Properties of the gas were found in [4] and are presented in Table 3.8.

Table 3.8: Heptane properties [4].

Properties	**Value**
Soot yield	3.7%
Heat of combustion	44600 Kg/kJ
Radiative Fraction	0.34

For the test, the total heat release rate from the fire was controlled by the following curve,

$$\dot{Q} = \dot{Q}_o \left(\frac{t}{\tau} \right)^2 \tag{3.10}$$

where $\dot{Q}_o = 10$ MW and $\tau = 75$ s. For the actual tests the fire growth curve was followed until a fire size was reached or the first sprinkler activated. For the case of the simulation, the information of the fire growth was available, and it was set to be 4.6 MW at 50 seconds following the same heat release curve.

3.3.3 Measuring Devices

Temperature devices were placed at all the points where indicated on the actual tests. Temperature and velocity slides have been placed along the center of the vent on the x and y planes and one near the ceiling on the z axis. Mass flow through vents is also measured.

3.3.4 Simulated Test Case

Four different scenarios will be simulated to investigate the influence of a vent on the sprinkler activation time. The first simulation takes into account the fusible vent and sprinklers. Second scenario will only include sprinklers and the third one only the vent will be present. A fourth scenario is included, and it assumes that the vent is open from the beginning of the fire. Table 3.9 shows an overview of the fire scenarios.

Table 3.9: Large Facility simulated scenarios. In test V0-SP, the vent is open at the beginning of the fire.

Test ID	**Sprinklers**	**Vent**
V-SP	X	X
NV-SP	X	-
V-NSP	-	X
V0-SP	X	X

3.3.5 Grid

Three different grids sizes are used in a sensitivity analysis to establish the best grid resolution. Table 3.10 shows these mesh sizes.

Table 3.10: Mesh sizes for the large facility fire.

Grid Number	**Cell Size (cm)**
1	20
2	17.5
3	15

The same procedure explained in section 3.2.5 will be used to find the deviation of each mesh and identify the best grid definition.

There is no an specific time for the test, the report states that a test has been completed when steady state conditions are reached. To define a simulation time, there has been a review of the experimental results of all tests to find out the longest time achieved. It has been found that activation of sprinklers for the heptane test do not exceed 7 minutes. For this reason a simulation time of 500 seconds or 8.3 minutes has been defined.

Chapter 4

Results

4.1 Reference Test Case

This section presents the sensitivity analysis and results of the reference tests discussed in the previous chapter. As a reference, Figure 4.1 shows the location of measurement points, sprinklers, vent and burner.

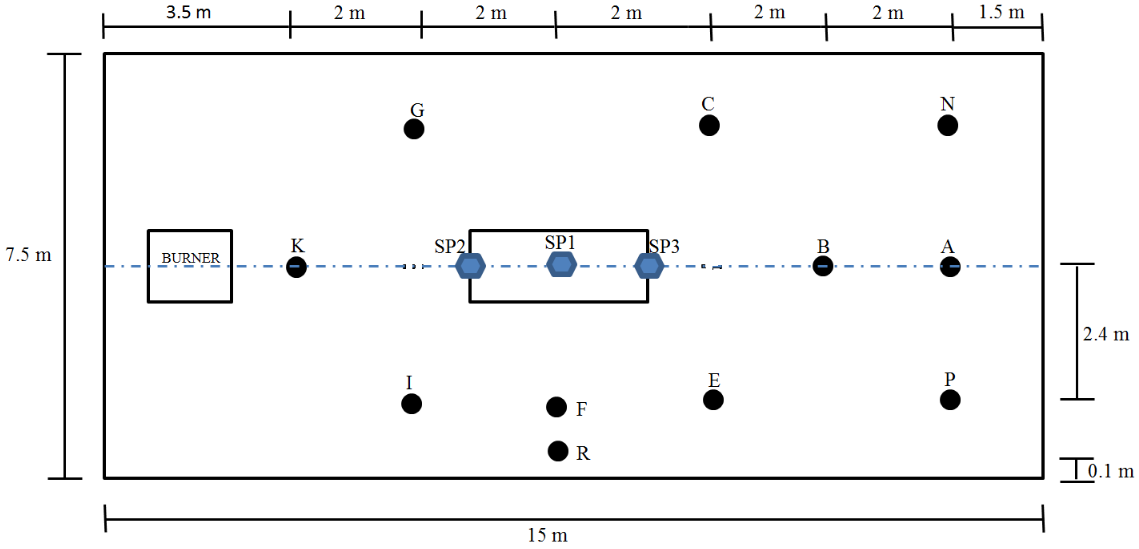


Figure 4.1: Reference test room measurement points location.

4.1.1 Sensitivity Analysis

Table 4.1a shows the deviation of each point following the procedure described in section 3.2.5. Comparing all the grids, it can be seen that the deviation for a grid of 10 cm is always lower for all the points.

Table 4.1b shows the sensitivity analysis for the velocity. It can be seen that the grid of 12.25 cm is the one that gives higher deviations. As with temperature, the 10 cm grid gives the lower values, most of them below 10%. The only point that presents considerable high values through all the grid, is point K, the one closer to the burner.

From these two tables it can be inferred that finer grids give better results. The deviation for the 10 cm is low (less than 10% for almost all points), for this reason

(a) Temperature sensitivity analysis.

Location	20 cm (%)	12.5 cm (%)	10 cm (%)
N	6.0	7.6	3.7
A	7.3	4.8	1.3
P	7.9	4.4	3
B	8.5	5.3	3.4
C	6.1	7.2	4.5
D	4.7	5.6	2.4
E	5.6	3.1	1.7
F	5.6	3.1	2.4
G	11.5	8.6	4.9
H	8.9	4.6	1.7
I	8.2	3.5	2.3
K	6.9	6.7	2.4
Average	7.3	5.4	2.8

(b) Velocity sensitivity analysis.

Location	20 cm (%)	12.5 cm (%)	10 cm (%)
N	3.7	6.2	2.9
A	6.6	8.0	3.3
P	5.7	4.9	3.3
B	8.1	9.2	5.2
C	4.7	9.9	3.2
D	5.9	7.6	4.2
E	5.7	9.0	3.6
F	8.1	11.2	2.9
G	7.4	8.0	7.7
H	6.8	12.2	5.8
I	8.8	10.2	6.3
K	13.5	22.4	12.6
Average	7.1	9.9	5.1

and for convenience on the computational time , the 10 cm grid will be used for all tests.

4.1.2 Temperature and Velocity profiles no vented case

Figures 4.2 to 4.5 show the temperature and velocities profiles of experiments and simulations for the no vented scenarios with a sprinkler at the center of the room (NV_SP1_0/80/100). The points presented in the figures correspond to locations where experimental velocity and temperature data were available. Results of simulations at other points can be consulted in Annex A.1.

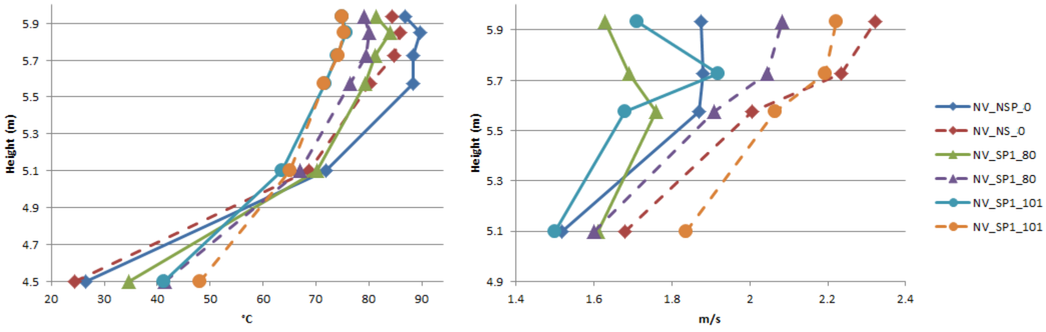


Figure 4.2: Temperature and velocity for Point A (Solid lines correspond to experiments, dashed lines to simulations).

Regarding temperatures, in most cases, simulated temperatures follow the same profile as tests. Most of the points show a deviation equal or less to 10%. The highest deviations are found at 4.5 m, where the smoke layer boundary is. Turbulence behavior and friction forces between these tow layers can explain this deviation. Figure 4.3 shows the simulated temperature profile through the whole height of the room for point A, where it can be seen that the boundary of both layers is somewhere between 4 and 5 m.

Regarding velocity, experiments and simulations present considerably differences in values and profiles. Two turbulent models (Smagorinsky and Dardoff) and a finer grid (5 cm) were tested to find the influence of this factors on the velocity values. However, no improvement on the accuracy of the values was obtained.

Considering only the experimental results, the velocity upstream the sprinkler spray is dependent of the flow, the higher the flow the higher the velocity reduction.

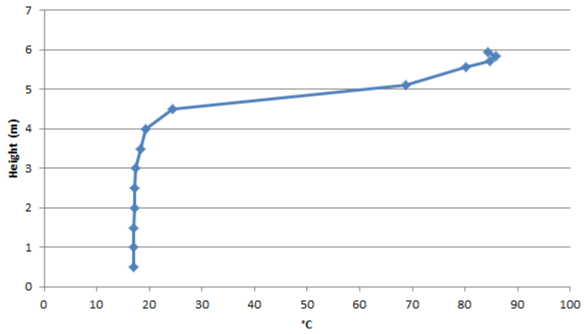


Figure 4.3: Temperature profile for the whole height for point A.

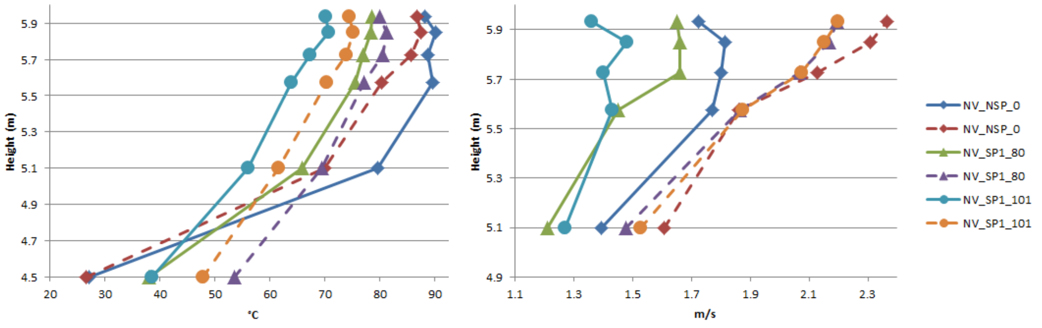


Figure 4.4: Temperature and velocity for Point B (Solid lines correspond to experiments, dashed lines to simulations).

For downstream locations , velocities were slightly reduced. However, due to some error in the data acquisition system, there are no enough values to drawn conclusions.

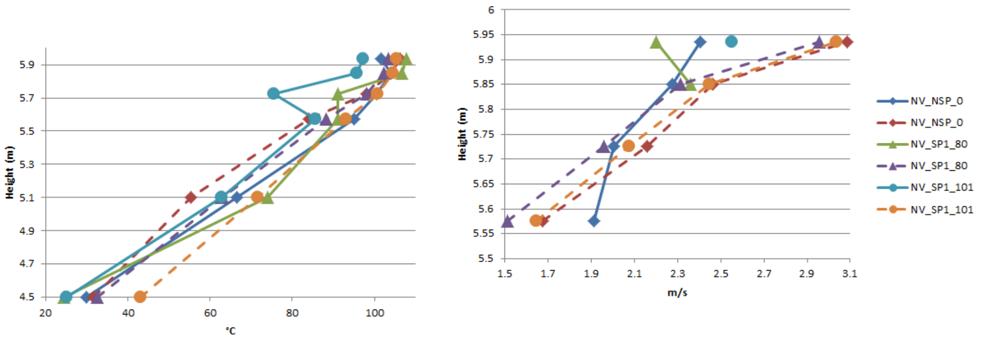
There are several possible factors than can influence the deviations obtained. One factor is the modeling of only the room and not the modeling of the whole test hall. Velocities in the hall were assumed to be 0 and ambient temperature was assumed to be a constant value of 290 K. Another source of deviation is the mechanical ventilation implemented in the actual tests. For the specified experiments there is no information about the flow used in the hall test. This flow may affect velocities at the room. Other source of error is the uncertainty in sprinklers parameters. Information about sprinkler specification is not available.

Finally, other possible error is the influence of water on the measuring devices. It is not known how thermocouples and pressure probes were influenced by water spray from the sprinklers.

4.1.3 Temperature and velocity values for the vented case

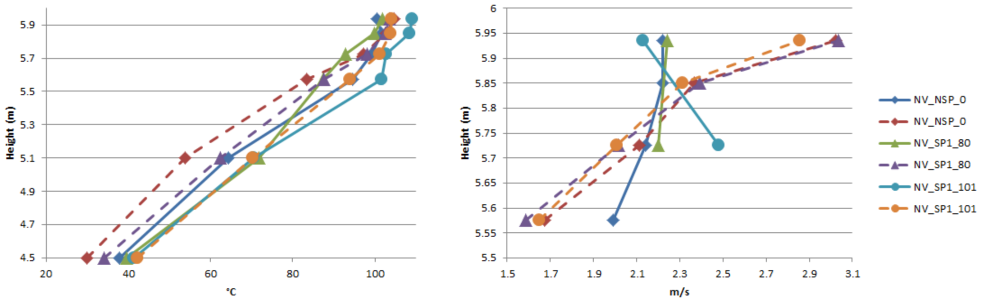
This section presents the experimental and simulated values for the vented tests including sprinklers SP3 and SP2. Experimental results of the central sprinkler are not reported due to an error in the data acquisition system. Figure 4.6 shows the location of the measurement points at the vent. In each point temperature and velocity was taken into account.

Figure 4.7 shows the experimental and simulated results of temperature and velocity for the test including a vent and a sprinkler 1 m downstream the center



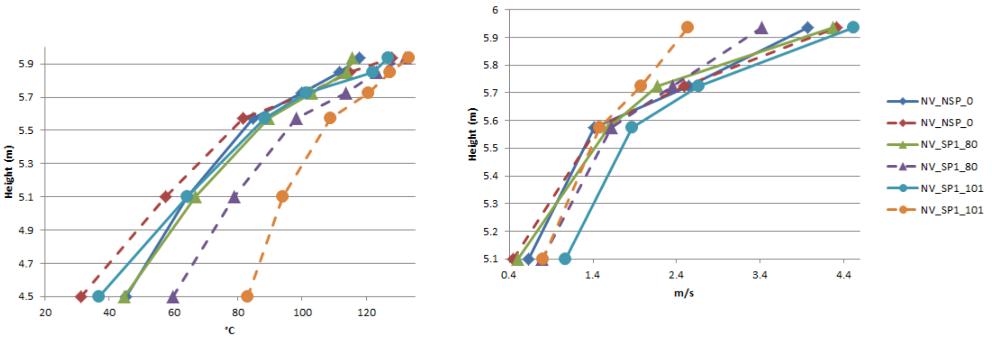
(a) Temperature at G.

(b) Velocity at G.



(c) Temperature at I.

(d) Velocity at I.



(e) Temperature at K.

(f) Velocity at K.

Figure 4.5: Temperature and velocity profiles for G, I and K (Solid lines correspond to experiments, dashed lines to simulations).

(V_SP2_0/80/101). Solid bars correspond to experimental values, textured bars represent simulated values.

Considering only the experimental results, the points closer to the fire (L1 and L3) are not affected by the action of the sprinkler. Points further from the fire (L2, L4, L5) are affected, and present a reduction on temperature and velocity when the flow is increased. It is important to note that there is air entering the vent at points L1 and L3 where the velocity is negative.

Simulations do not show a good agreement with actual tests, especially for velocity at locations closer to the fire. However, some points do follow the same reduction pattern with respect with tests. A wider area surrounding the room was also implemented to investigate the effect of it on vent measurements. No differences in results were found.

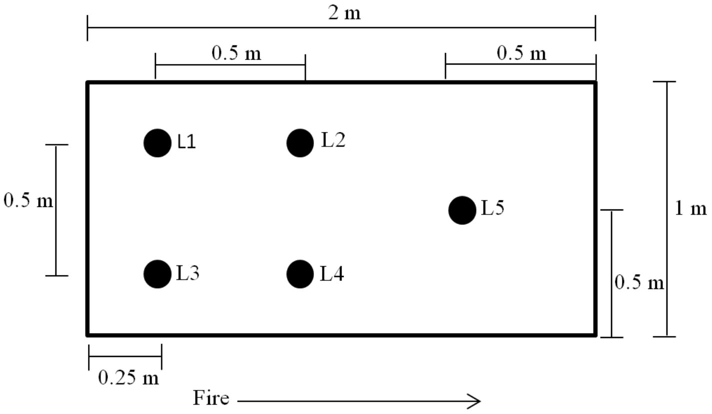


Figure 4.6: Vent measurement points.

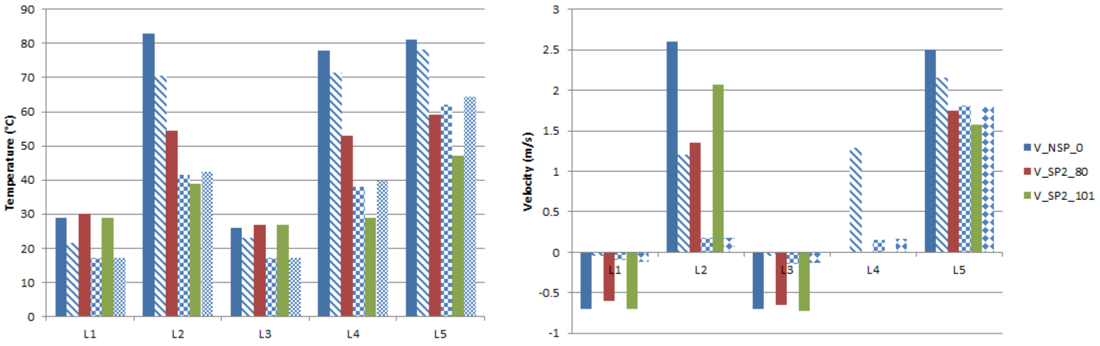


Figure 4.7: Experimental and simulated results for vent with Sp2.

Figure 4.8 shows the experimental and simulated results of temperature and velocity for the test including a vent and a sprinkler 1 m upstream the center (V_SP3_0/80/100).

It is clear here that the effect on temperature and velocity of the sprinkler located downstream the vent, is rather low compared with the sprinkler located upstream. For points closer to the fire (L1-L4) there is a slightly increase in temperatures when the flow is increased. For L5 the reduction in temperature and velocity is more significant.

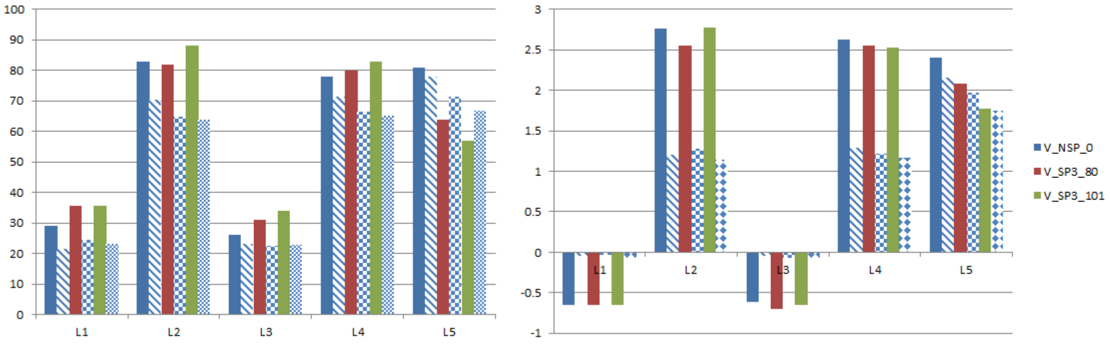


Figure 4.8: Experimental and simulated results for vent with Sp3.

4.1.4 Deviation of the simulated values

For a better understanding of the differences obtained in the simulation, a deviation will be calculated and presented in each measurement point. Deviation is calculated with the following formula,

$$D_T = \frac{|T_{sim} - T_{exp}|}{T_{exp}}; D_U = \frac{|U_{sim} - U_{exp}|}{U_{exp}} \tag{4.1}$$

where T_{sim} is the simulated temperature and T_{exp} is the value obtained from actual tests. The same is valid for velocities. An average will be obtained for each point and then presented in a plot.

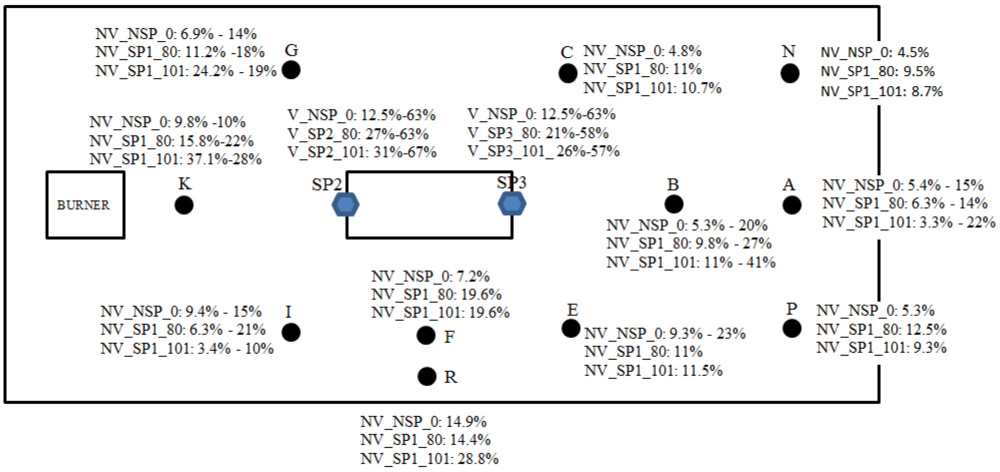


Figure 4.9: Temperature and Velocity deviation for the Reference Test(First number indicates temperature. Second number, velocity.)

Figure 4.9 shows the average deviation of all points in the test room. The first value corresponds to temperature and the second one to velocity. As it can be seen, the points farther from the fire (N,A,P) present the lower deviation for both parameters, also points at both sides of the wall present a good symmetry.

For points C,B and E, deviation is low for the case with no sprinkler. When sprinklers are activated, deviation increases up to 11%. For velocities at point B, deviation is quite high, especially for the sprinkler with a flow of 101 L/min.

Points F and R are the ones that present the higher deviation of all the points, however, as reported in [9], these points were in contact with water and actual gas measurements can be influenced by this fact.

The closest point to the fire (point K), has also a high deviation, this can be explained due to the combustion model used, and the proximity of the point to the modeled flame.

Deviations at the vent are very high compared with the ones inside the room. It also can be notice that deviation do not vary a lot from sprinklers location.

4.1.5 Temperature and Velocity Relation

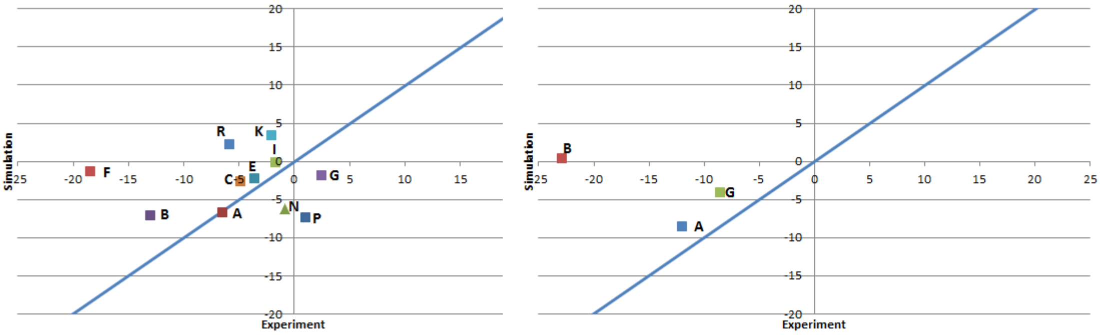
4.1.5.1 No vented case

Even though in some cases the simulation values do not show a very good agreement with experimental values, they do present a pattern of reduction or increment. These patterns will be explained and studied next.

For the case of the no vented scenario with no sprinkler (NV_NSP_0), the highest experimental value at each point has been selected to be compared with the other scenarios at the same height. The relation is given by,

$$D_T = \frac{(T_{sc} - T_{ref})}{T_{ref}} \times 100; D_U = \frac{(U_{sc} - U_{ref})}{U_{sc}} \times 100 \tag{4.2}$$

where T_{sc} and U_{sc} are the temperature and velocity values of the scenario to be compared. T_{ref} and U_{ref} are the highest temperature and velocity values of the reference scenario (NV_NSP_0) and are called reference values. The complete data from all the tests can be found in Annex D.



(a) Temperature.

(b) Velocity.

Figure 4.10: Reduction relation for NV_SP1_80.

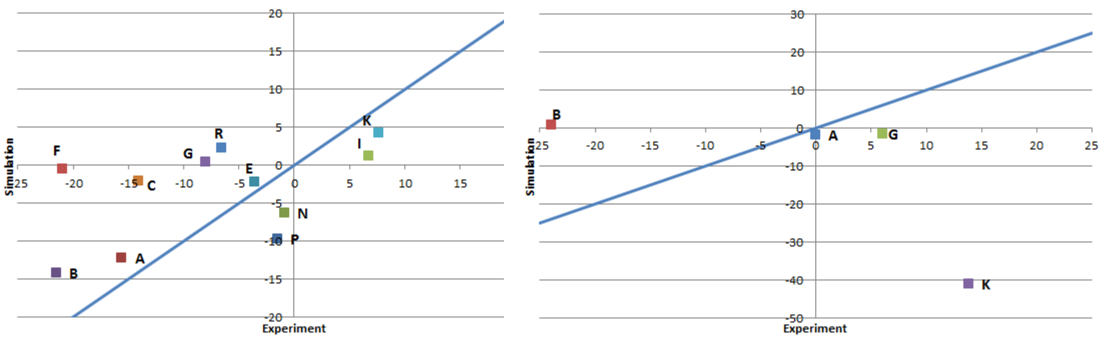
Figure 4.10 shows the relation in reduction or increase for experimental and simulated values. For the temperature, it can be observed that most of the points are on the negative quadrant, which means that simulations predicted the reduction produced by the experiment. However, some of these points are far from the line, specifically points F and B.

Points R, K, G and P are locations where the simulation did not predict the same pattern. It is important to notice that this points are located close to the walls with exception of point K, which is located in front of the burner.

There is not too much information for velocity. Nevertheless simulations predicted a reduction similar to experiments with exception of point B, which is very far from the experimental value.

Figure 4.11 shows the relation for experimental and simulated values of the fire with the sprinkler at the center of the room and a flow of 101 L/min (NV_SP1_101).

The relation for temperature (see Figure 4.11a) presents higher values than for a sprinkler with 80 L/min. As it can be seen, the points are spread along the line, in contrast with Figure 4.10a, where points are concentrated at the center of the plot. Points F, C, G and R are the ones farther from the line, and all are located closer



(a) Temperature.

(b) Velocity.

Figure 4.11: Experiment and simulation relation for NV_SP1_101.

to the walls of the room. Again points R and F are the ones with higher differences between experiments and simulations.

Regarding velocity, differences between experiments and simulations are quite high. The only agreement is with point A, where the reduction is almost negligible. Once again, there is not enough points for more consistent conclusions.

4.1.5.2 Vented case

The same procedure has been followed for the vented scenario. In this case the scenario of the room with a vent and no sprinkler (V_NSP_0) has been selected as the reference case.

Figure 4.12 shows the relation of the measurement points for all the available vented scenarios. It is important to notice that data for the sprinkler at the center of the vent is not available due to an error in the data acquisition system.

Regarding temperature, it can be seen that for the case where the sprinkler is located upstream the vent, simulations predict the reduction for points L1, L4 and L5. These points are located near the center of the vent. Points L2 and L3, which are close to the edge of the vent, do not show a good agreement. For the sprinkler located downstream the vent, points that show a good agreement are L1 and L5. However, for the rest of locations, simulations do not predict the reduction obtained in experiments.

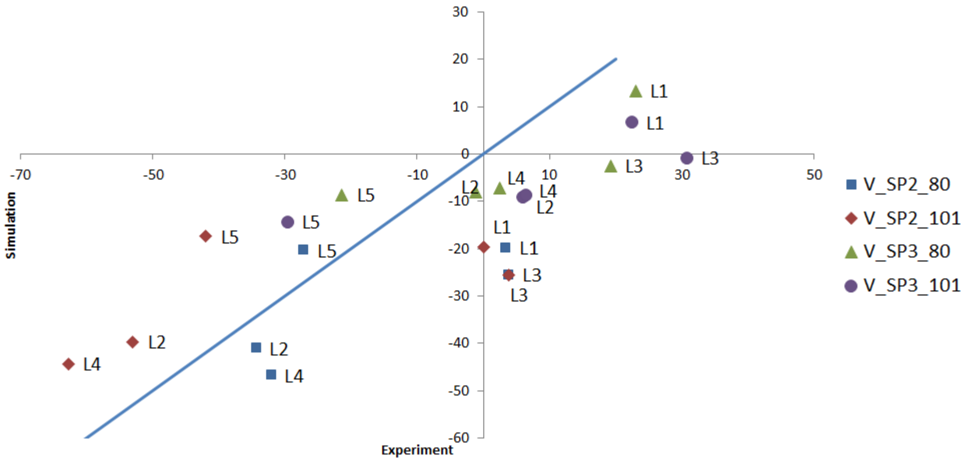
For velocities at both scenarios (SP1 and SP2), points L2, L4 and L5 shows a good relation. Points L1 and L3, which are at the edge of the vent present large differences between the experimental and simulated values.

4.1.5.3 Simulated cases

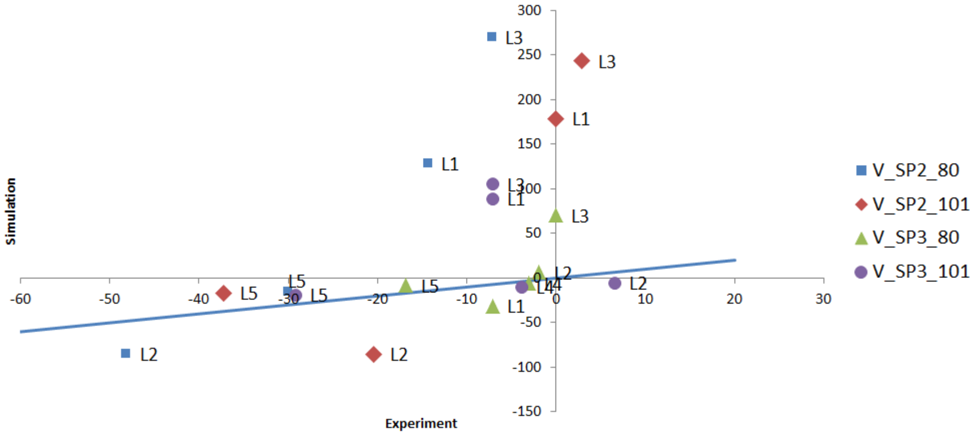
Figure 4.13 shows the simulated reduction or increment for all the points in the room. The first column of numbers correspond to temperature changes, the second column to velocity changes. This figure presents all the simulated scenarios.

4.1.6 Temperature and Velocity Profiles

Figures 4.14 and 4.15 present the temperature and velocity profiles at the center of the room. The first column of pictures make reference to the no vented case. The



(a) Temperature relation.



(b) Velocity reduction.

Figure 4.12: Reduction relation for the vented scenario.

second column presents the same fire scenario but including a vent.

4.1.7 Mass flow through Vent

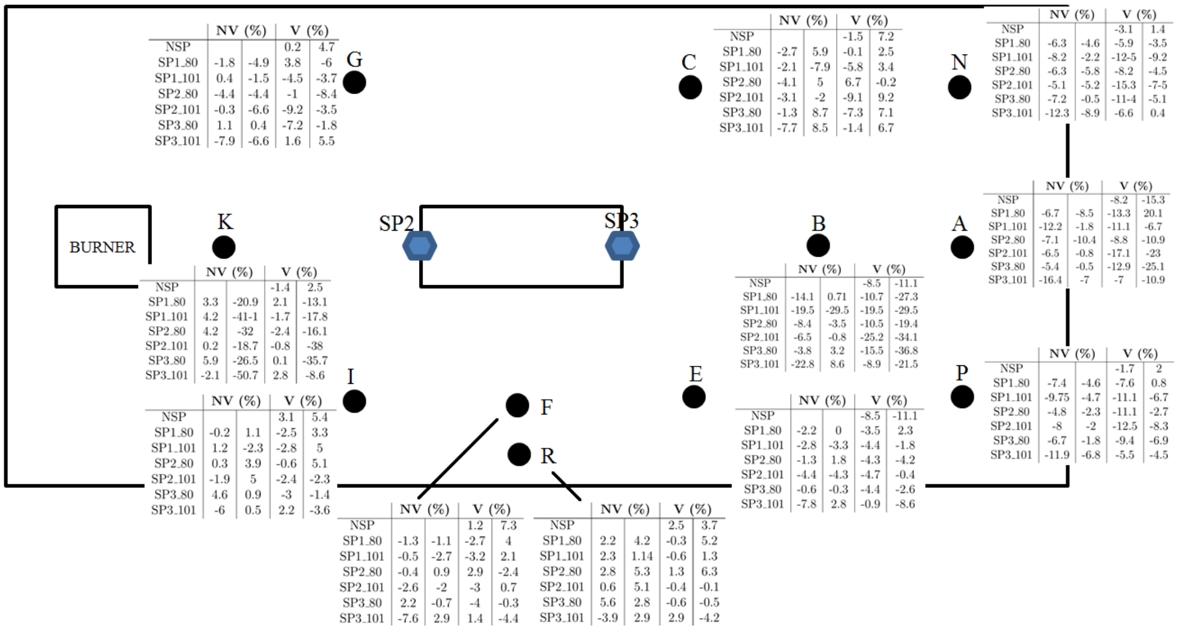
Mass flow through vents has been measured for all simulated scenarios and the result is presented in Figure 4.16.

A comparison with the theoretical value, given by equation 2.1 presented in section 2.2.2.1 (and shown next) is also done.

$$\dot{m} = \frac{C A_v \rho_\infty \sqrt{2gd\Delta T T_\infty}}{T_\infty + \Delta T} \tag{4.3}$$

where C is an orifice coefficient equal to 0.6, A_v is the area of the vent (2 m^2), p is the density of air (1.2 kg/m^3), g is gravity (9.8 m/s^2), d is the depth of the layer of the hot gases (from Figure 4.3 is 1.5 m), ΔT is the average temperature rise in the layer (48.5°K), and T_∞ is the ambient temperature which is 290°K.

Replacing the values above into equation 4.3, the maximum theoretical mass flow through the vent is equal to 2.73 kg/m^2. This value is presented in Figure 4.16 as a green dashed line.



	NV (%)		V (%)	
NSP			0.2	4.7
SP1_80	-1.8	-4.9	3.8	-6
SP1_101	0.4	-1.5	-4.5	-3.7
SP2_80	-4.4	-4.4	-1	-8.4
SP2_101	-0.3	-6.6	-9.2	-3.5
SP3_80	1.1	0.4	-7.2	-1.8
SP3_101	-7.9	-6.6	1.6	5.5

	NV (%)		V (%)	
NSP			-1.5	7.2
SP1_80	-2.7	5.9	-0.1	2.5
SP1_101	-2.1	-7.9	-5.8	3.4
SP2_80	-4.1	5	6.7	-0.2
SP2_101	-3.1	-2	-9.1	9.2
SP3_80	-1.3	8.7	-7.3	7.1
SP3_101	-7.7	8.5	-1.4	6.7

	NV (%)		V (%)	
NSP			-3.1	1.4
SP1_80	-6.3	-4.6	-5.9	-3.5
SP1_101	-8.2	-2.2	-12-5	-9.2
SP2_80	-6.3	-5.8	-8.2	-4.5
SP2_101	-5.1	-5.2	-15.3	-7-5
SP3_80	-7.2	-0.5	-11-4	-5.1
SP3_101	-12.3	-8.9	-6.6	0.4

	NV (%)		V (%)	
NSP			-8.2	-15.3
SP1_80	-6.7	-8.5	-13.3	20.1
SP1_101	-12.2	-1.8	-11.1	-6.7
SP2_80	-7.1	-10.4	-8.8	-10.9
SP2_101	-6.5	-0.8	-17.1	-23
SP3_80	-5.4	-0.5	-12.9	-25.1
SP3_101	-16.4	-7	-7	-10.9

	NV (%)		V (%)	
NSP			-1.4	2.5
SP1_80	3.3	-20.9	2.1	-13.1
SP1_101	4.2	-41-1	-1.7	-17.8
SP2_80	4.2	-32	-2.4	-16.1
SP2_101	0.2	-18.7	-0.8	-38
SP3_80	5.9	-26.5	0.1	-35.7
SP3_101	-2.1	-50.7	2.8	-8.6

	NV (%)		V (%)	
NSP			-8.5	-11.1
SP1_80	-14.1	0.71	-10.7	-27.3
SP1_101	-19.5	-29.5	-19.5	-29.5
SP2_80	-8.4	-3.5	-10.5	-19.4
SP2_101	-6.5	-0.8	-25.2	-34.1
SP3_80	-3.8	3.2	-15.5	-36.8
SP3_101	-22.8	8.6	-8.9	-21.5

	NV (%)		V (%)	
NSP			-1.7	2
SP1_80	-7.4	-4.6	-7.6	0.8
SP1_101	-9.75	-4.7	-11.1	-6.7
SP2_80	-4.8	-2.3	-11.1	-2.7
SP2_101	-8	-2	-12.5	-8.3
SP3_80	-6.7	-1.8	-9.4	-6.9
SP3_101	-11.9	-6.8	-5.5	-4.5

	NV (%)		V (%)	
NSP			3.1	5.4
SP1_80	-0.2	1.1	-2.5	3.3
SP1_101	1.2	-2.3	-2.8	5
SP2_80	0.3	3.9	-0.6	5.1
SP2_101	-1.9	5	-2.4	-2.3
SP3_80	4.6	0.9	-3	-1.4
SP3_101	-6	0.5	2.2	-3.6

	NV (%)		V (%)	
NSP			-8.5	-11.1
SP1_80	-2.2	0	-3.5	2.3
SP1_101	-2.8	-3.3	-4.4	-1.8
SP2_80	-1.3	1.8	-4.3	-4.2
SP2_101	-4.4	-4.3	-4.7	-0.4
SP3_80	-0.6	-0.3	-4.4	-2.6
SP3_101	-7.8	2.8	-0.9	-8.6

	NV (%)		V (%)	
NSP			1.2	7.3
SP1_80	-1.3	-1.1	-2.7	4
SP1_101	-0.5	-2.7	-3.2	2.1
SP2_80	-0.4	0.9	2.9	-2.4
SP2_101	-2.6	-2	-3	0.7
SP3_80	2.2	-0.7	-4	-0.3
SP3_101	-7.6	2.9	1.4	-4.4

	NV (%)		V (%)	
NSP			2.5	3.7
SP1_80	2.2	4.2	-0.3	5.2
SP1_101	2.3	1.14	-0.6	1.3
SP2_80	2.8	5.3	1.3	6.3
SP2_101	0.6	5.1	-0.4	-0.1
SP3_80	5.6	2.8	-0.6	-0.5
SP3_101	-3.9	2.9	2.9	-4.2

Figure 4.13: Relation for simulated scenarios.

As it can be seen, the no sprinklered case is very close to the theoretical value. When sprinklers are used, efficiency of the vent is lowered. Upstream sprinklers reduce the efficiency 36% no matter the flow. Centered sprinklers also reduce the efficiency to values close to the upstream sprinklers (Sp1). However, for this case, an increase of the flow clearly presents a drastic reduce (51%). Downstream sprinkler (Sp3) presents the better efficiency for the mass flowing out the vent.

4.2 Large Facility Fire

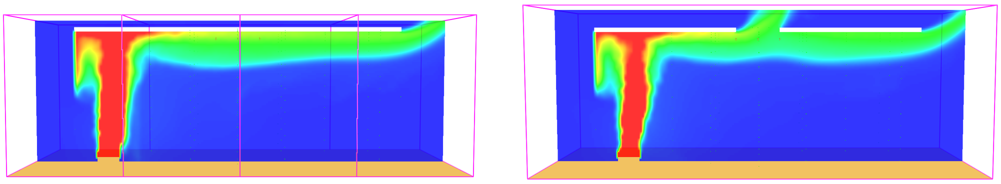
4.2.1 Sensitivity Analysis

According to section 3.3.5, a grid sensitivity analysis has been done to identify the differences between grid sizes. Figure 4.17 shows the deviation temperature of the different thermocouples located next to sprinklers. The first number corresponds to the deviation of the 17.5 cm grid with respect to a 1 cm grid size. Second number corresponds to the deviation of the 20 cm grid.

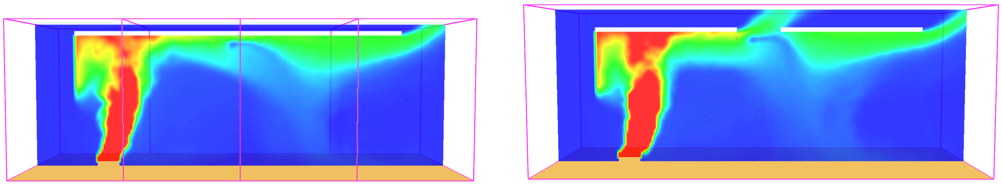
As it can be seen, the deviation is high close to the burner (letter C) and the 20 cm grid shows lower values at this region. Points far from the fire source present low deviations especially for the grid of 17.5 cm. Taking into account these values and the computational time required to perform these simulations, a grid of 20 cm will be used for the study case.

4.2.2 Sprinklers Activation Times

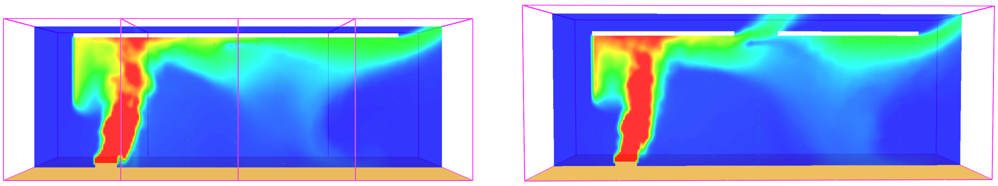
Figure 4.18 shows the sprinkler activation time for the experiment and the multiple simulated scenarios. The number enclosed in a rectangle corresponds to the experimental value. As expected, the first sprinklers to activate are the ones closer the fire. Experimental times present a difference between the sprinklers located at the



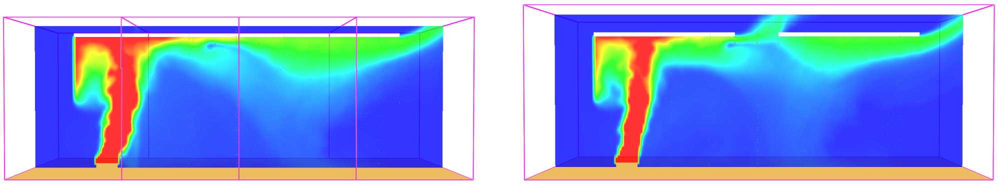
(a) NV_NSP_0. (b) V_NSP_0.



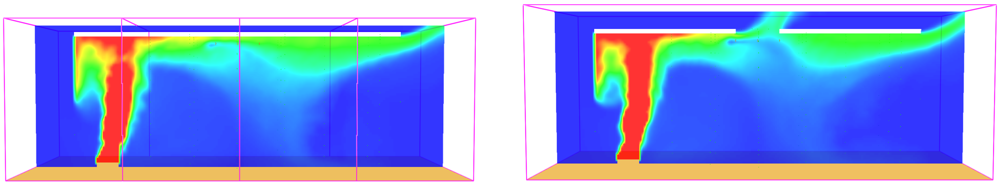
(c) NV_SP1_80. (d) V_SP1_80.



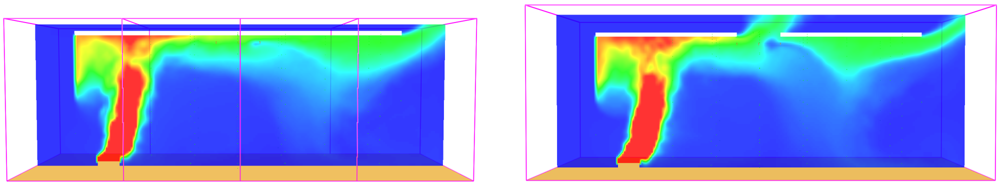
(e) NV_SP1_101. (f) V_SP1_101.



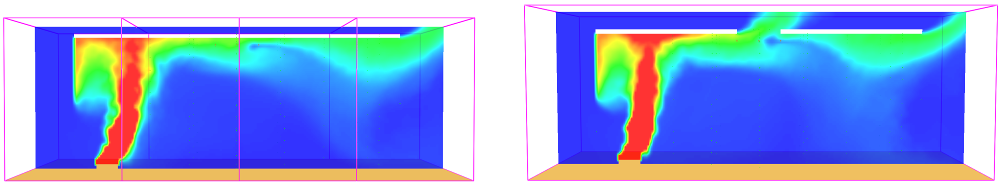
(g) NV_SP2_80. (h) V_SP2_101.



(i) NV_SP2_101. (j) V_SP2_101.



(k) NV_SP3_80. (l) V_SP3_80.



(m) NV_SP3_101. (n) V_SP3_101.

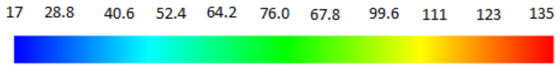
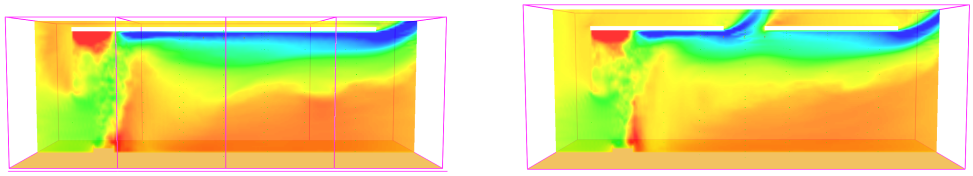
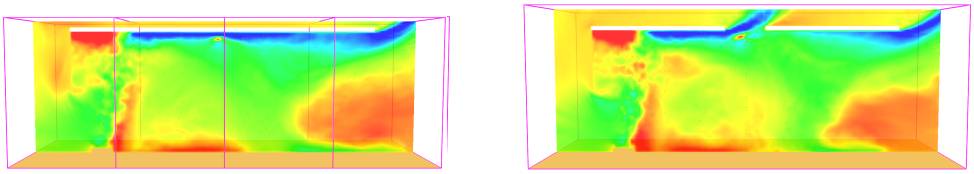


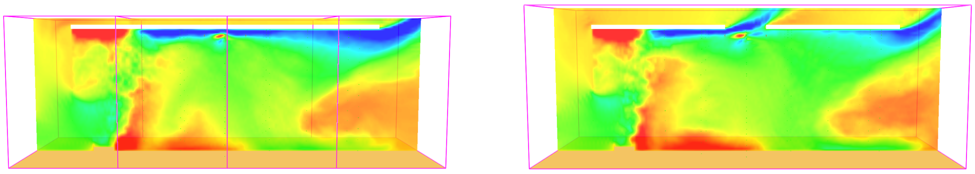
Figure 4.14: Temperature slides for the reference case.



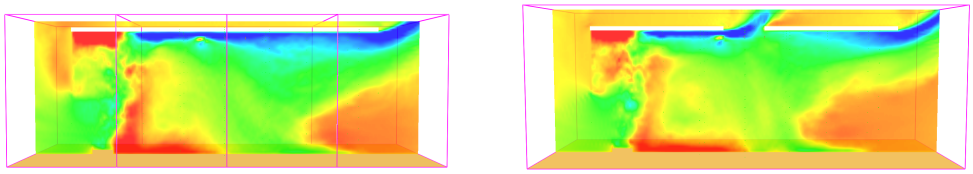
(a) NV_NSP_0. (b) V_NSP_0.



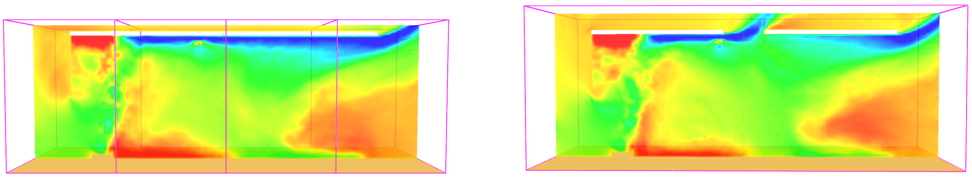
(c) NV_SP1_80. (d) V_SP1_80.



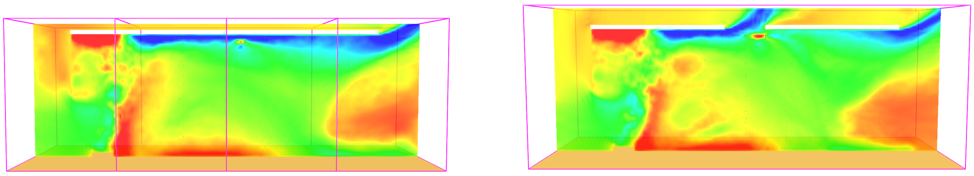
(e) NV_SP1_101. (f) V_SP1_101.



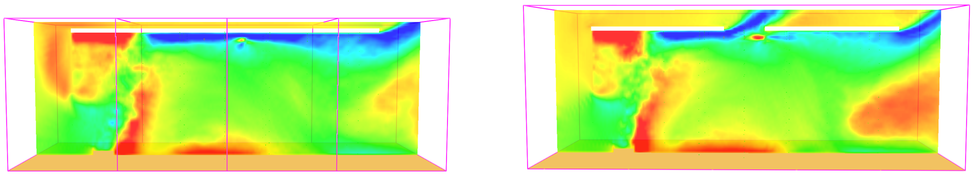
(g) NV_SP2_80. (h) V_SP2_101.



(i) NV_SP2_101. (j) V_SP2_101.



(k) NV_SP3_80. (l) V_SP3_80.



(m) NV_SP3_101. (n) V_SP3_101.

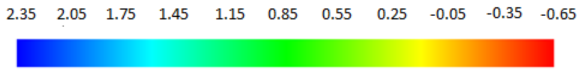


Figure 4.15: Velocity slides for the reference case.

lower part of the fire and the upper part, this can be due to the smoke extraction system and its influence on the air flow.

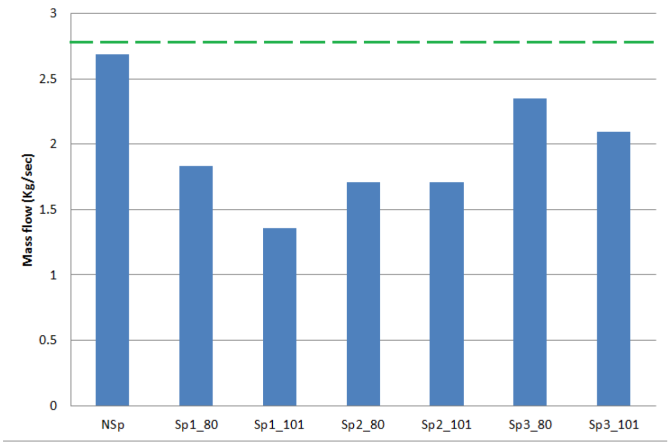


Figure 4.16: Mass flow through vent. The dashed line represents the theoretical value from Equation 4.3.

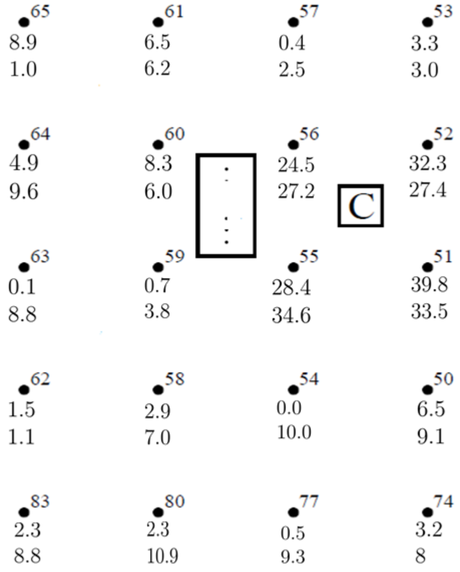


Figure 4.17: Sensitivity analysis for the Large Facility Fire

Simulation predicts with good agreement the activation time of the first two sprinklers, giving a difference of 2 seconds. For the upper sprinklers, the model tends to underestimate the activation time with a difference between 12 and 18 seconds. For the outer ring of sprinklers, the model presents only one activation long time after the first sprinklers have activated. However, it is important to notice that the vent in the experiment, did open only after 7 minutes, therefore, the experiment can also be compared with the no vented scenario, since all sprinklers activated before 7 minutes. Even in this scenario, activation is not well predicted since only two sprinklers activated at the outer ring.

Grid size might be one of the causes of the no prediction of the activation of the outer ring sprinklers. However, it is important to notice that according to Figure 4.17, deviation at this region is relatively low, which would mean that using a finer grid will still no predict the activation of sprinklers. From Annex B it can be seen that some temperatures near sprinklers are lower than the calculated deviation and they could not reach the sprinkler activation temperature. This can also be addressed to the sensitivity of the particle size in sprinkler modeling. This is mentioned in the report [11] and also in O'grady et al. [14]. From this two studies it can be inferred that sprinklers particle size is a very sensible parameter in this type of studies.

The modeled activation time of the vent is quite different to the experimental one. For the model, the activation occurs one minute after the fire has started, however, for the experiment the activation occurs after 7 minutes. Examining other tests reported, it is clear that even though the fusible link reaches its activation temperature at about the same time as the first sprinkler activation, the link in some cases did not fuse, on others took a lot of time to melt. The causes are not known but it can be due to water cooling the link, or a malfunctioning link.

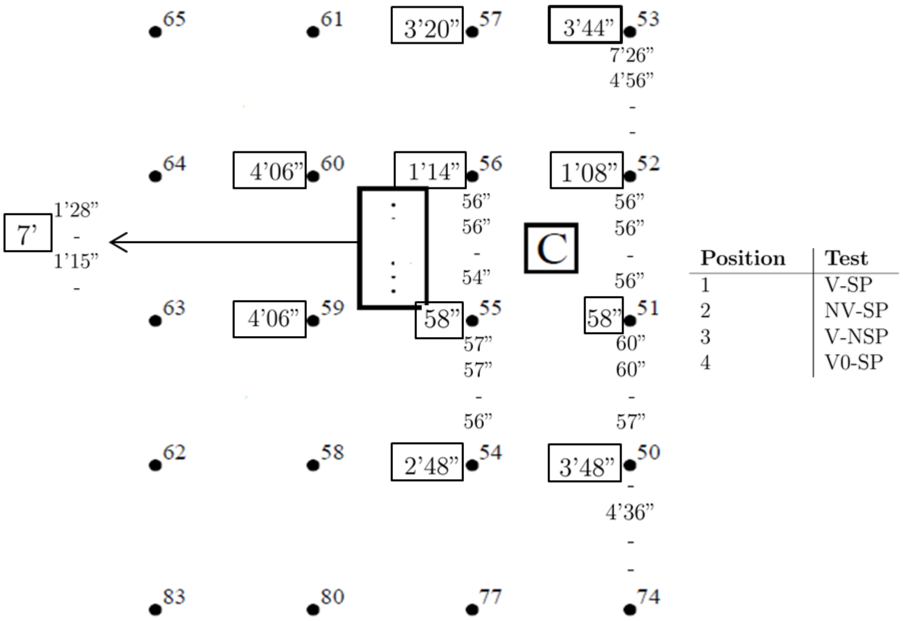


Figure 4.18: Sprinkler activation time. Numbers inside a box correspond to the experimental value.

4.2.3 Mass flow

The theoretical value is given by equation 4.3. For this case the values obtained from the simulations are presented in table 4.2 giving as a result a theoretical mass flow of 2.76 kg/s.

Table 4.2: Values for the theoretical mass flow

Variable	**Value**
C	0.6
A_v	2.88 m^2
ρ_∞	1.2 kg/m^3
d	0.5 m
ΔT	91 °K
T_∞	290 °K

From Figure 4.19 it is clear that with the absence of sprinklers, the mass flow reaches its maximum value, which is close to the theoretical one (dashed line). For this case, opening the vent at the beginning of the fire does not make any significant difference in the mass flow extracted.

Comparing the theoretical mass flow (2.76 kg/s) and the average mass flow of the simulated scenario (1.79 kg/s), there is a reduction of 35% which is a very similar reduction found in the Reference Test Case (36%, see Section 4.1.7) when a upstream sprinkler was used.

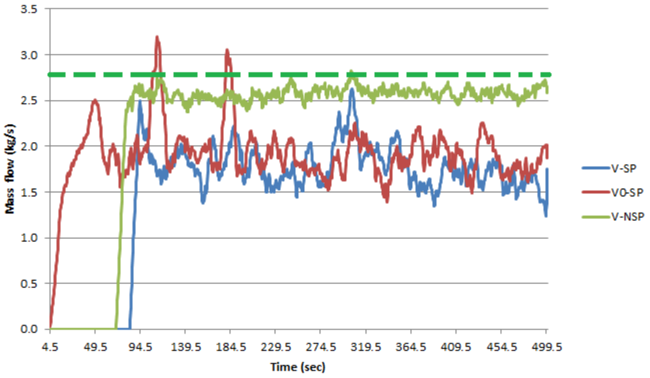


Figure 4.19: Mas flow rate for the large facility fire.

Figure 4.20 shows the mass flow for the case where a fusible vent and sprinklers were used (V-SP). What intents to show this figure is the effect that has a single sprinkler on the mass flow. The vertical solid line indicates the activation of the sprinkler number 53. As it can be seen, after sprinkler activation the mass flow is reduced. This shows that even a sprinkler that is not located between the fire and the vent, can have an influence in the smoke extracted.

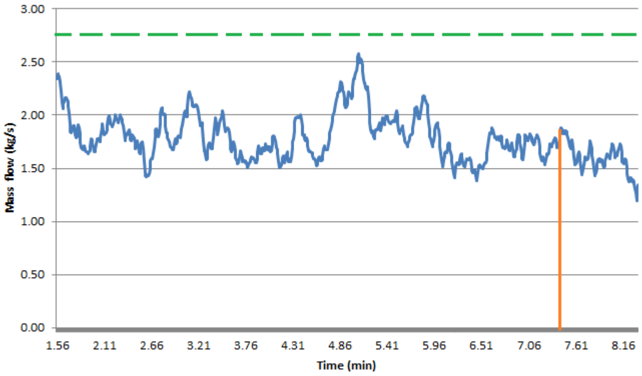
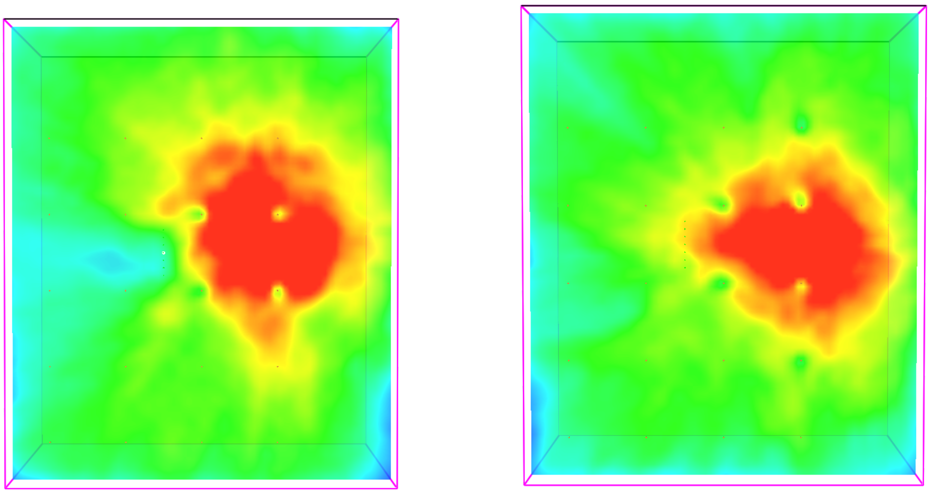


Figure 4.20: Influence of a sprinkler on the mass flow rate. The solid line indicates the activation of sprinkler 53; the dashed line, the theoretical value of maximum smoke extraction.

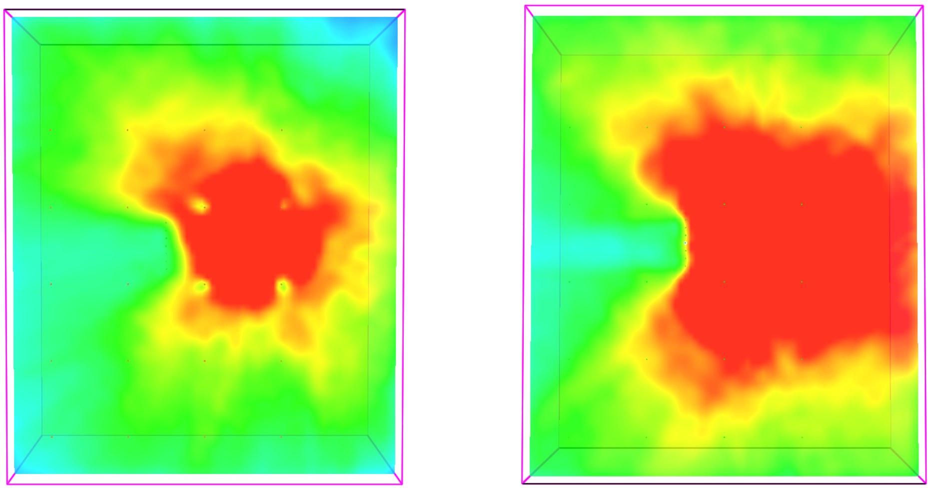
4.2.4 Temperature Profile near Ceiling

Figure 4.21 shows the temperature profiles near the ceiling at a height of 7.5 m. When the vent is open, the reduction in temperature is clear downstream the vent.

When sprinkler are not used there is a wider area where the temperature is over 100 °C.



(a) Vent and Sprinkler (b) Sprinkler and no vent.



(c) Vent (no fusible link) and Sprinkler (d) Vent and no Sprinklers.

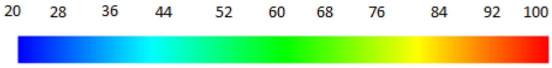


Figure 4.21: Temperature slides near the ceiling.

Chapter 5

Discussion

In the previous chapter, experimental and simulated results were presented for a reference test and for a large domain test including an array of sprinklers. For the former, a single sprinkler at several locations was tested and velocity and temperature measurements were taken. For the later, vent opening times and sprinkler activation times were studied at different conditions. In this chapter, results are analyzed based on the effect that has each protection device on the other and the surroundings in terms of temperature, velocity and mass flow changes.

5.0.5 Effect of Sprinklers on the Room

Regarding temperatures in the reference test, for downstream locations (points A and B), experiments and simulations show a very clear reduction in temperature. For upstream locations (points G,I and K) the reduction is not clear, moreover, experiments and simulations show that at some locations, temperature increases few degrees.

Ingason [9] described this increment as a *3-dimensional blocking effect* which can be identified on the temperature and velocity slides presented in the previous chapter. Figure 4.15 shows that the sprinkler creates a barrier that blocks the income of air from the right side of the room and make horizontal velocity below it close to 0. This blocking effect hinders the normal flow of hot gases leading to an increase of temperature at the region close to the fire.

Regarding velocities, due to problems in the pressure probes, there is no sufficient experimental data to analyze the effect that sprinklers has on it. However, the available measurements show that downstream, velocities are reduced as the sprinkler water flow increases.

As explained before, the model could predict the temperature measurements in most of the locations. As Figure 4.9 shows, the deviation is below 10% for locations far from the fire and the sprinkler (points N, A, and P). Locations that are closer to the sprinkler (points F and R) are the ones that present the higher deviation. This might be due to the fact that in the actual tests, instrumentation at these locations were in contact with water, and this can affect the measurement of actual gas temperatures. From this same graph, it can be seen that point K, the one closer to the fire, also presents a high deviation. This can be explained due to the simple combustion model used and the proximity of the point to the modeled flame.

It is also important to show here, that the highest deviations occur when the sprinklers are activated and the water flow increases. Based on sensitivity analysis done by [14] and [11] it seems that the particle size is a very sensitive parameter in the modeling of sprinklers that might affect the outcome of a simulation, and this is reflected here.

Finally, Figure 4.13 also shows that simulations predict the reduction in temperatures for all downstream locations and an increment at some locations upstream.

5.0.6 Effect of a Vent on the Room

Unfortunately there is no experimental data available to analyze what happens inside the room when a vent is used, therefore, this analysis will be based on modeled results. As expected and based on Figure 4.13, temperature is reduced in locations downstream the vent and the reduction is grater at the room centerline where the vent is located. For upstream locations, temperature has a slight increase for points close to the walls and a reduction at the center of the room.

Velocities present an increment for upstream locations and for points downstream there is no an specific pattern, in one side of the wall a reduction is found and on the other side an increment is found. However, at the center line, the reduction is considerably high.

Also as it is shown in Figure 4.14, it is clear how the hot gas layer is reduced when a vent is used, thus confirming the functionality of the device.

5.0.7 Effect of the sprinkler location on the room

Based on Figures 4.14 and 4.15, there is no a significant difference in temperatures or velocities profiles when the sprinkler location is changed. The more noticeable fact is that the *sprinkler blocking effect* tends to move to the side where the sprinkler is located.

5.0.8 Effect of Sprinkler Flow and Location on the Vent

Taking into account Figures 4.7 and 4.8 and based on the experimental data, it can be seen that when the sprinkler is located upstream the vent, temperature and velocity are significantly reduced.

For the sprinkler located downstream, there is no an appreciable effect on the temperature and velocity at the measured points, which means that the influence of a sprinkler located downstream is less considerable when located upstream.

The model does not show a good agreement with experimental values, and it can be seen from Figure 4.9, that deviation at the vent is higher than 10% for all the cases and it reaches values up to 31%.

In despite of this high deviation, the model can predict with good agreement a reduction or increment at certain points. Figure 4.12 shows that temperature reduction at point L5, L2 and L4 are very similar between experiments and simulations. So is the increment of point L1. For velocities, points L5 and L2 present a good agreement.

Besides temperatures and velocities, mass flow was also measured in the model. From Figure 4.16 it can be inferred that no matter the location of the sprinkler, there is always a reduction of the mass flow extracted by it. However, the upstream and the centered sprinklers are the ones that have a higher effect on the reduction of the mass flow. An increase on the water flow also has an effect on the extraction, the higher the flow, the less hot air extracted. Table 5.1 shows the percentage of reduction of mass flow extracted for each case. As it can be seen the lower reduction in efficiency is achieved when the sprinkler is located downstream.

As mentioned in the literature review (section 2.2.1.3), using the zone model software SPLASH, a reduction in efficiency using a single sprinkler was reported to be 14%, which based on Table 5.1 could be the case where a sprinkler is located downstream the vent. Unfortunately there is no more information available about the model, therefore a further analysis cannot be done.

Table 5.1: Mass flow percentage of reduction

Case	**%**
NSp	-
Sp1_80	31
Sp1_101	49
Sp2_80	36
Sp2_101	36
Sp3_80	12
Sp3_101	21

5.0.9 Effect of Vent on Sprinkler Activation Times

Based on Figure 4.18, it is clear that the vent does not influence the activation of the first ring of sprinklers. However, when the vent is not open, the second ring of sprinklers presented two activations 4 minutes after the fire had started. Opening the vent right after the fire has started, does not have any influence on the sprinkler activation time. These results imply that vents help to activate sprinklers located only close to the fire.

5.0.10 Effect of a Sprinkler Array on the Mass Flow Extracted

Figure 4.19 shows the mass flow extracted by the vent for different scenarios in the large facility fire. As it can be seen, when sprinklers are not activated, mass flow reaches a value close to the theoretical value given by Hinkley in [4]. When sprinklers are activated, the extracted mass flow is reduced by an average value of 1.79 kg/s. Comparing this value with the no sprinklered scenario, the reduction is equal to 32%, which is a value close to the one obtained for the reference case with upstream sprinklers.

This means that for this case, an array of sprinklers located upstream the vent have a similar reduction that a single sprinkler located upstream a vent.

Another important founding is the one shown by Figure 4.20. The vertical line indicates the time when a sprinkler of the outer ring activates. When this happens, the mass flow is reduced. This will imply that even a sprinkler that is far apart from the fire and the vent, can influence the amount of smoke extracted by the vent.

Chapter 6

Conclusions

Two numerical models based on actual experiments were developed to study the interaction between sprinklers and natural vents. The first model intended to investigate the effect of a single sprinkler at different locations and water flows on a single vent. The second model was developed to study the influence of a single vent on sprinkler activation times, but also the effect of a sprinkler array on the efficiency of a vent. The analysis of the experiments and the model has drawn the following conclusions:

- The test and the model simulations showed that location of the sprinkler is a determinant factor regarding vent efficiency. Upstream sprinklers presented the highest reduction in temperature, velocity and mass flow extracted at the vent. Downstream sprinkler showed to have the lowest impact on vent efficiency.

- The test and the model showed that water mass flow also has an impact on vent efficiency, especially for sprinklers located upstream. Higher flows presented a higher temperature and vertical velocities reductions at the vent, thus reducing mass flow.

- Model simulations showed that there is no a significant effect on sprinkler activation times when a vent is opened before or after first sprinkler activation. However, based on other tests done in [11], this is only valid for fires that are not directly under a vent.

- Model simulations showed that for fires with a constant HRR, vents allow the activation of sprinklers located close to the fire. Sprinklers far away from the fire were no activated.

- For all scenarios and based on the model simulations, sprinklers always reduced the mass flow extracted by vents.

- Based on the results obtained in this thesis, the model could predict near ceiling temperatures showing deviations lower than 10% when sprinkler were not activated. However, for velocities, the model presented poor agreement with experimental data.

- Modeling of sprinklers presents the highest deviation when compared with experimental data. There are several parameters that are very sensitive and affect significantly the results. e.g. particle velocity and particle size.

Experimental data regarding interaction of sprinklers and vents is still scarce. More experiments need to be done for a better understanding of the problem. As Heselden stated [5], the interaction between this two protection systems is very complex and depends on many factors. Numerical models appear to be an ideal solution to predict the general characteristics of this interaction. Nevertheless, more validation needs to be done in order increase the model accuracy.

Acknowledgments

This thesis would have not been possible without the help and support from my supervisor Dr. Tarek Beji. My sincerest gratitude for his guidance and support throughout all this process. Especial thanks to Prof. Bart Merci, his support on finding the needed documentation for this thesis was essential.

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From March 1979

Weary of all who come with words, words but no language
I make my way to the snow-covered island.
The untamed has no words.
The unwritten pages spread out on every side!
I come upon the tracks of deer in the snow.
Language but no words.

Tomas Tranströmer

Bibliography

[1] Craig L. Beyler and Leonard Y. Cooper. "Interaction of Sprinklers with Smoke and Heat Vents". In: *Fire Technology* 37.1 (). Ed. by Kluwer Academic Publishers, pp. 9–35.

[2] WK Chow and YL Cheung. "Simulation of sprinkler—hot layer interaction using a field model". In: *Fire and Materials* 18.6 (), pp. 359–379.

[3] Leonard Y Cooper. "Estimating the environment and the response of sprinkler links in compartment fires with draft curtains and fusible link-actuated ceiling vents—Theory". In: *Fire Safety Journal* 16.2 (), pp. 137–163.

[4] Philip J DiNenno. *SFPE handbook of fire protection engineering.* SFPE.

[5] AJM Heselden. *The Interaction of Sprinklers and Roof Venting in Industrial Buildings: The Current Knowledge.* Department of the Environment, Building Research Establishment, Fire Research Station.

[6] PL Hinkley. "The Effect of Smoke Venting on the Operation of Sprinklers Subsequent to the First". In: *Fire safety journal* 14.3 (), pp. 221–240.

[7] PL Hinkley. "The effect of vents on the opening of the first sprinklers". In: *Fire safety journal* 11.3 (), pp. 211–225.

[8] PL Hinkley et al. "Large-Scale Experiments with Roof Vents and Sprinklers". In: *Fire Science and Technology* 13.1/2 (), 1_19–1_41.

[9] H. Ingason and S. Olsson. *Interaction between sprinklers and fire vents.* Ed. by The Swedish National Testing SP-REPORT 1992:11 and Research Institute. Boras, Sweden.

[10] KY Li et al. "Experimental investigation on drag effect of sprinkler spray to adjacent horizontal natural smoke venting". In: *Journal of hazardous materials* 174.1 (). Ed. by Elsevier, pp. 512–521.

[11] KB McGrattan, A Hamins, and DW 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.* NISTIR.

[12] Kevin McGrattan et al. "Fire dynamics simulator, user's guide". In: ().

[13] Kevin McGrattan et al. "Fire dynamics simulator (version 6), technical reference guide". In: *NIST special publication* 1018 ().

[14] Neal O'Grady and Vasily Novozhilov. "Large eddy simulation of sprinkler interaction with a fire ceiling jet". In: *Combustion Science and Technology* 181.7 (), pp. 984–1006.

[15] Bror Persson and Haukur Ingason. *Modelling of Interaction Between Sprinklers and Fire Vents: Present Knowledge.* Ed. by Swedish National Testing and Research Institute. Boras, Sweden.

[16] Hsieh Tung-Liang et al. "The Effect of Smoke Vents on the Sprinklers in a Small Compartment". In: *Journal of Applied Fire Science* 11.2 (). Ed. by Baywood, pp. 91–119.

[17] Heimo Tuovinen. "Validation of ceiling jet flows in a large corridor with vents using the CFD code JASMINE". English. In: *Fire Technology* 32.1 (), pp. 25–49.

[18] William D Walton and EK Budnick. "Deterministic computer fire models". In: *Fire Protection Handbook,* ().

Appendix A

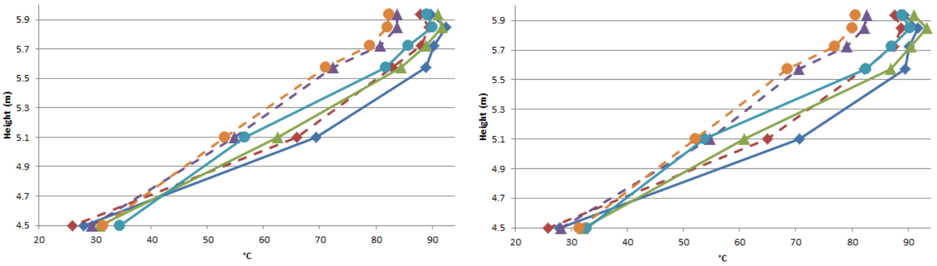
Temperature and velocity profiles

A.1 Tests and Simulations graphs for test NV_SP_0-80-101

Results of temperatures and velocities profiles of simulations are presented next. Location of the points can be found in Figure 4.1. Table A.1 shows the convention of the graphs. Solid lines correspond to actual tests values, dashed lines to simulations.

Table A.1: Convention for temperature and velocity profiles.

ID of test	**Symbol**
NV_NSP_0	♦
NV_SP1_80	▲
NV_Sp1_101	●



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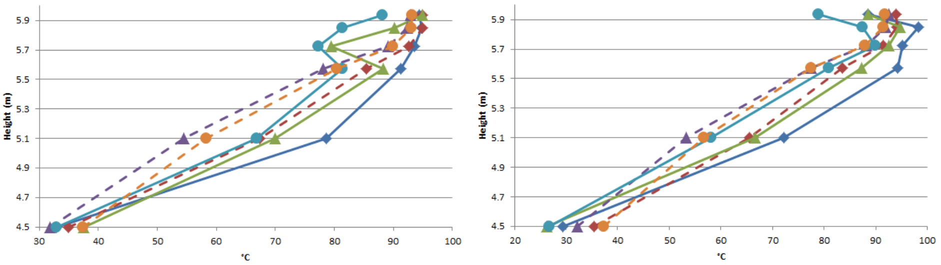
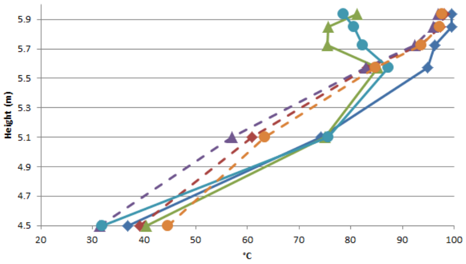
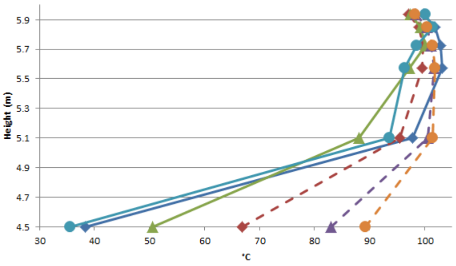


(a) C (b) E


5.9
5.7
5.5
5.3
5.1
4.9
4.7
4.5
Height (m)
20
30
40
50
60
70
80
90
100
°C

(a) F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5.7
5.5
5.3
5.1
4.9
4.7
4.5
Height (m)
30
40
50
60
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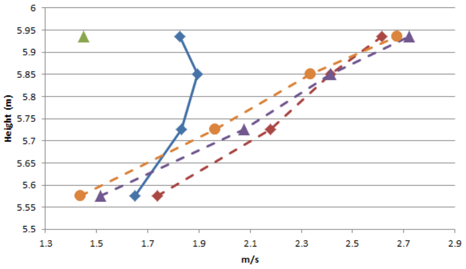
80
90
100
°C

(b) R


6
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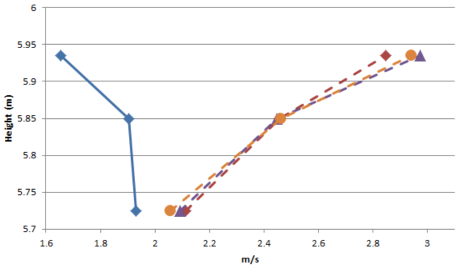
5.9
5.85
5.8
5.75
5.7
5.65
5.6
5.55
5.5
Height (m)
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
m/s

(c) E

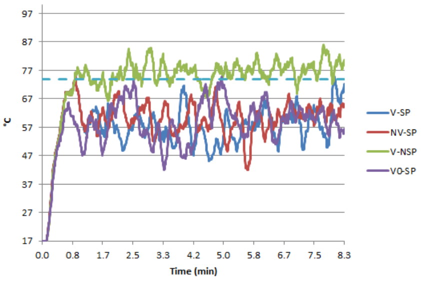

6
5.95
5.9
5.85
5.8
5.75
5.7
Height (m)
1.6
1.8
2
2.2
2.4
2.6
2.8
3
m/s

(d) F

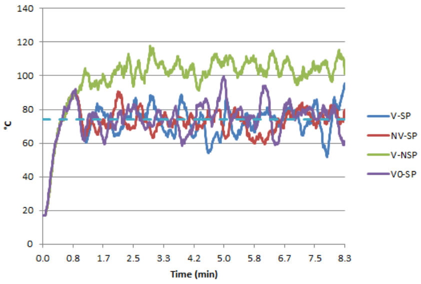
Appendix B

Temperature near sprinklers - Large Scale Fire

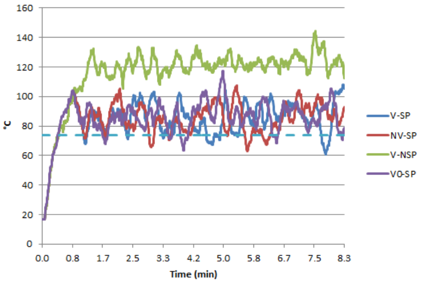
This annex presents the temperature near sprinklers for the four scenarios. The dashed line corresponds to the sprinkler activation temperature. The graphs are presented on the same format of the report for comparison purposes.



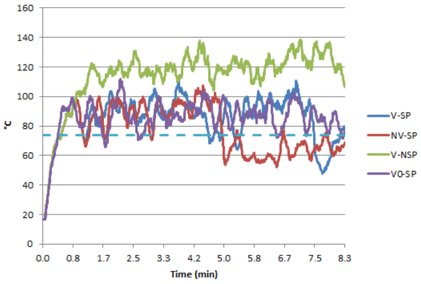
(a) 65



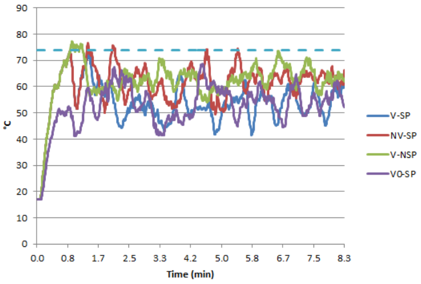
(b) 61



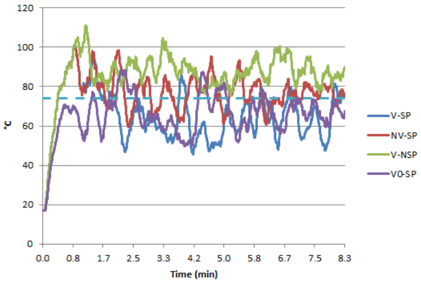
(c) 57



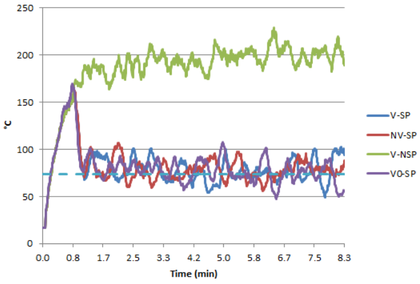
(d) 53



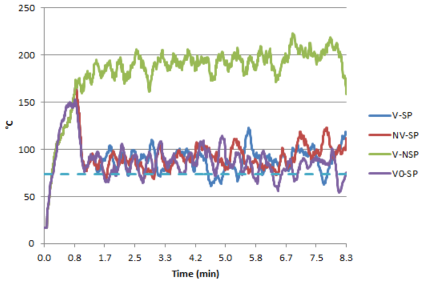
(e) 64



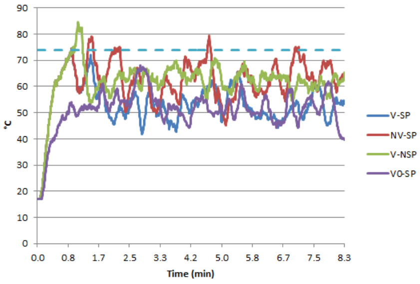
(f) 60



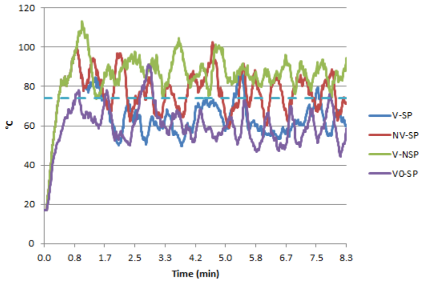
(g) 56



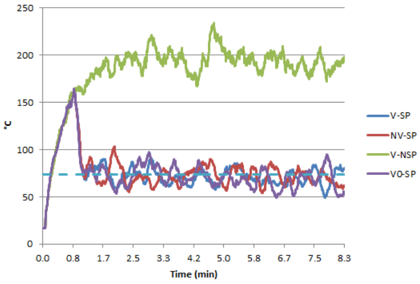
(h) 52



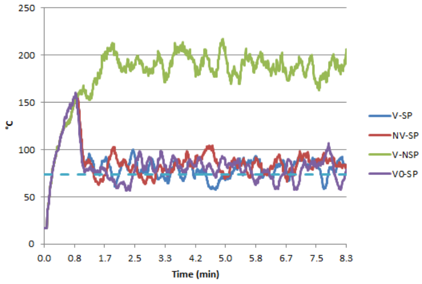
(i) 63



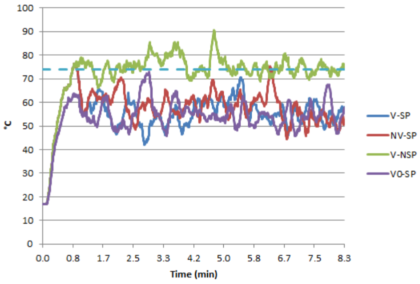
(j) 59



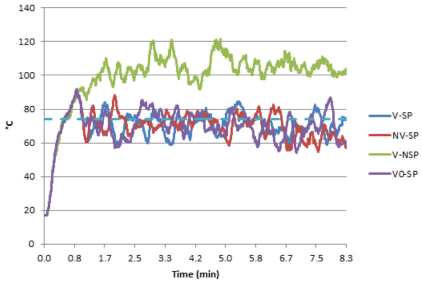
(k) 55



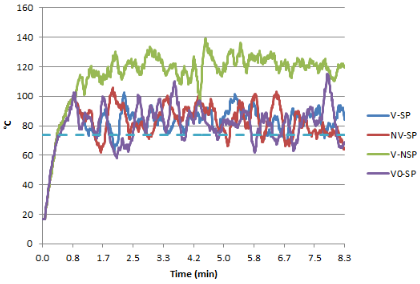
(l) 51



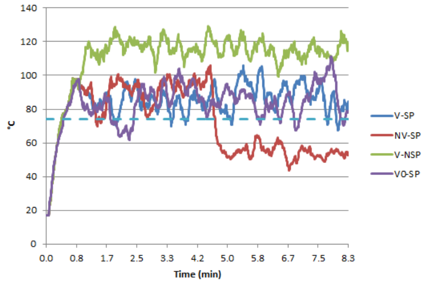
(m) 62



(n) 58



(o) 54



(p) 50

Appendix C

FDS Codes

C.1 Reference test case

```
TEST 00
&HEAD CHID = ’1smg’, TITLE =’NO SPRINKLER - NO VENT - FINE MESH’/
&MESH ID=’a’ IJK = 47,75,65, XB=0.0,4.7,0.0,7.5,0.0,6.5, COLOR=’BLACK’/
&MESH ID=’b’ IJK = 47,75,65, XB=4.7,9.4,0.0,7.5,0.0,6.5, COLOR=’BLUE’/
&MESH ID=’c’ IJK = 47,75,65, XB=9.4,14.1,0.0,7.5,0.0,6.5, COLOR=’GREEN’/
&MESH ID=’d’ IJK = 47,75,65, XB=14.1,18.8,0.0,7.5,0.0,6.5, COLOR=’RED’/
&TIME T_END=540/
&DUMP DT_RESTART=20/
&MISC TMPA=17.0, RESTART=.TRUE./
&SPEC ID=’WATER VAPOR’/
&RADI RADIATIVE_FRACTION=0.31/
```

BURNER

```
&REAC ID=’PROPANE’
SOOT_YIELD=0.024
C=3.
H=8.
HEAT_OF_COMBUSTION=46450
IDEAL=.TRUE./
&SURF ID=’BURNER’, HRRPUA=1500.,COLOR=’RASPBERRY’/
&OBST XB= 15.0,16.0,3.2,4.2,0.0,0.2, SURF_IDS=’BURNER’,’INERT’,INERT/
&OBST XB= 15.0,16.0,3.2,3.2,0.2,0.4, SURF_ID=’INERT’/
&OBST XB= 15.0,15.0,3.2,4.2,0.2,0.4, SURF_ID=’INERT’/
&OBST XB= 15.0,16.0,4.2,4.2,0.2,0.4, SURF_ID=’INERT’/
&OBST XB= 16.0,16.0,3.2,4.2,0.2,0.4, SURF_ID=’INERT’/
```

MATERIAL

```
&MATL ID=’GYPSUM’, CONDUCTIVITY=0.12, SPECIFIC_HEAT=0.8, DENSITY=780. /
&SURF ID=’GYPSUM CEILING’, MATL_ID=’GYPSUM’, BACKING=’EXPOSED’, THICKNESS=0.095/
```

```
&SURF ID=’GYPSUM WALL’, MATL_ID=’GYPSUM’, BACKING=’EXPOSED’,
THICKNESS=0.13 /
```

WALLS

```
&OBST XB=2.0,17.0,0.0,0.0,0.0,6.0, SURF_ID=’GYPSUM WALL’ / FRONT
&OBST XB=2.0,17.0,7.5,7.5,0.0,6.0, SURF_ID=’GYPSUM WALL’ / BACK
&OBST XB=17.0,17.0,0.0,7.5,3.0,6.0, SURF_ID=’GYPSUM CEILING’ / RIGHT
&OBST XB=2.0,17.0,0.0,7.5,6.0,6.2, SURF_ID=’GYPSUM CEILING’ / CEILING
&HOLE XB=8.5,10.5,3.2,4.2,5.9,6.3/
```

VENTS

```
&VENT XB=0.0,18.8,0.0,7.5,6.5,6.5,SURF_ID=’OPEN’/TOP VENT
&VENT XB=0.0,18.8,0.0,0.0,0.0,6.5,SURF_ID=’OPEN’/FRONT VENT
&VENT XB=0.0,18.8,7.5,7.5,0.0,6.5,SURF_ID=’OPEN’/BACK VENT
&VENT XB=18.8,18.8,0.0,7.5,0.0,6.5,SURF_ID=’OPEN’/RIGHT VENT
&VENT XB=0.0,0.0,0.0,7.5,0.0,6.5,SURF_ID=’OPEN’/LEFT VENT
```

SPRINKLER

```
&PART ID=’water drops’, SPEC_ID=’WATER VAPOR’,DIAMETER=500., /
&PROP ID=’K-80’,
PART_ID=’water drops’,
K_FACTOR=80,
OPERATING_PRESSURE=1.0,
PARTICLE_VELOCITY=5.58,
SMOKEVIEW_ID=’sprinkler_pendent’,
SPRAY_ANGLE=65.,115./
&DEVC ID=’Spr_60’, XYZ=9.5,3.75,5.66, PROP_ID=’K-80’, QUANTITY=’TIME’,
SETPOINT=303/
```

```
&PART ID=’water drops’, SPEC_ID=’WATER VAPOR’,DIAMETER=500., /
&PROP ID=’K-80’,
PART_ID=’water drops’,
K_FACTOR=80,
OPERATING_PRESSURE=1.0,
PARTICLE_VELOCITY=5.58,
SMOKEVIEW_ID=’sprinkler_pendent’,
SPRAY_ANGLE=65.,115./ &DEVC ID=’Spr_60’, XYZ=8.5,3.75,5.66, PROP_ID=’K-
80’, QUANTITY=’TIME’, SETPOINT=542/
```

```
&PART ID=’water drops’,
SPEC_ID=’WATER VAPOR’,DIAMETER=500., /
&PROP ID=’K-80’,
PART_ID=’water drops’,
K_FACTOR=80,
OPERATING_PRESSURE=1.0,
PARTICLE_VELOCITY=5.58,
```

```
SMOKEVIEW_ID='sprinkler_pendent',
SPRAY_ANGLE=65.,115./
&DEVC ID='Spr_60', XYZ=10.5,3.75,5.66, PROP_ID='K-80', QUANTITY='TIME',
SETPOINT=542/
```

MEASURES

TEMPERATURE

```
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&DEVC XYZ=11.5,6.15,5.575, QUANTITY=’U-VELOCITY’, ID=’I4’/
&DEVC XYZ=11.5,6.15,5.725, QUANTITY=’U-VELOCITY’, ID=’I3’/
&DEVC XYZ=11.5,6.15,5.85, QUANTITY=’U-VELOCITY’, ID=’I2’/
&DEVC XYZ=11.5,6.15,5.935, QUANTITY=’U-VELOCITY’, ID=’I1’/
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&DEVC XYZ=13.5,3.75,2.0, QUANTITY=’U-VELOCITY’, ID=’K11’/
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&DEVC XYZ=13.5,3.75,3.5, QUANTITY=’U-VELOCITY’, ID=’K8’/
&DEVC XYZ=13.5,3.75,4.0, QUANTITY=’U-VELOCITY’, ID=’K7’/
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&DEVC XYZ=13.5,3.75,5.575, QUANTITY=’U-VELOCITY’, ID=’K4’/
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&DEVC XYZ=13.5,3.75,5.85, QUANTITY=’U-VELOCITY’, ID=’K2’/
&DEVC XYZ=13.5,3.75,5.935, QUANTITY=’U-VELOCITY’, ID=’K1’/
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&DEVC XYZ=9.75,3.95,6.2, QUANTITY=’W-VELOCITY’, ID=’L1’/
&DEVC XYZ=10.25,3.45,6.2, QUANTITY=’W-VELOCITY’, ID=’L4’/
```

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&DEVC XYZ=9.0,3.7,6.2, QUANTITY=’W-VELOCITY’, ID=’L5’/

MASS FLOW

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&DEVC XB=17.0,17.0,0.0,7.5,0.0,3.0, QUANTITY=’MASS FLOW’, ID=’RIGHT’/

SLIDES

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&SLCF PBY=3.7, QUANTITY=’U-VELOCITY’, ID=’VEL ROOM’/

&TAIL/
```

C.2 Industrial Fire

```
TEST 00
&HEAD CHID = ’1’, TITLE =’SPRINKLER - FINE MESH’/
&MESH IJK = 75,90,45, XB=0.0,15.0,0.0,17.9,0.0,9, /
&TIME T_END=600/
&DUMP DT_RESTART=10/
&MISC TMPA=17.0, RESTART=.TRUE./
&SPEC ID=’WATER VAPOR’/
&RADI RADIATIVE_FRACTION=0.34/

BURNER

&REAC ID=’HEPTANE’
SOOT_YIELD=0.037
C=7.
H=16.
HEAT_OF_COMBUSTION=44600
IDEAL=.TRUE./
&SURF ID=’BURNER’, HRRPUA=4600.,COLOR=’RASPBERRY’, TAU_Q= 50.31/
&OBST XB= 8.5,9.5,8.5,9.5,0.0,0.6, SURF_IDS=’BURNER’,’INERT’,INERT/

MATERIAL

&MATL ID=’GYPSUM’, CONDUCTIVITY=0.0611, SPECIFIC_HEAT=0.753, DENSITY=313. /
&SURF ID=’GYPSUM CEILING’, MATL_ID=’GYPSUM’, BACKING=’EXPOSED’, THICKNESS=0.16/
&MATL ID=’METAL’, CONDUCTIVITY=30, SPECIFIC_HEAT=0.45, DENSITY=7850. /
&SURF ID=’CURTAIN’, MATL_ID=’GYPSUM’, BACKING=’EXPOSED’, THICKNESS=0.00121/
```

WALLS

```
&OBST XB=0.0,15.0,0.0,17.9,7.6,7.9, SURF_ID=’GYPSUM CEILING’ / CEILING
```

VENTS

```
&VENT XB=0.0,15,0.0,17.9,9,9,SURF_ID=’OPEN’/TOP VENT
&VENT XB=0.0,15.0,0.0,0.0,0.0,9,SURF_ID=’OPEN’/FRONT VENT
&VENT XB=0.0,15,17.9,17.9,0.0,9,SURF_ID=’OPEN’/BACK VENT
&VENT XB=15,15,0.0,17.9,0.0,9,SURF_ID=’OPEN’/RIGHT VENT
&VENT XB=0.0,0.0,0.0,17.9,0.0,9,SURF_ID=’OPEN’/LEFT VENT
&HOLE XB=5.4,6.6,7.8,10.2,7.4,8.0, COLOR=’GREEN’, DEVC_ID=’LINK’/
&DEVC XYZ=6,9,7.58, PROP_ID=’LINK1’, ID=’LINK’, INITIAL_STATE=.FALSE.
/
&PROP ID=’LINK1’, QUANTITY=’LINK TEMPERATURE’, ACTIVATION_TEMPERATURE
= 74., RTI=175./
```

SPRINKLER

```
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&PROP ID=’K-11.4’,
QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=1.5,1.5,7.5, PROP_ID=’K-11.4’/
```

```
&PART ID=’water drops’, SPEC_ID=’WATER VAPOR’,DIAMETER=1000., /
&PROP ID=’K-11.4’,
QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=4.5,1.5,7.5, PROP_ID=’K-11.4’/
```

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&PART ID=’water drops’, SPEC_ID=’WATER VAPOR’,DIAMETER=1000., /
```

```
&PROP ID=’K-11.4’,
QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
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```

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&PROP ID=’K-11.4’,
QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=10.5,1.5,7.5, PROP_ID=’K-11.4’/
```

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QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
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RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
```

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K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
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SPRAY_ANGLE=5.,80./
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QUANTITY=’SPRINKLER LINK TEMPERATURE’,
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PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=7.5,4.5,7.5, PROP_ID=’K-11.4’/
```

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&PART ID=’water drops’, SPEC_ID=’WATER VAPOR’,DIAMETER=1000., /
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QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=10.5,4.5,7.5, PROP_ID=’K-11.4’/
```

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RTI=148,
C_FACTOR=0.7,
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K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
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```

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RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=4.5,7.5,7.5, PROP_ID=’K-11.4’/
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QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
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RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=10.5,7.5,7.5, PROP_ID=’K-11.4’/
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&PROP ID=’K-11.4’,
QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
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K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=1.5,10.5,7.5, PROP_ID=’K-11.4’/
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QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=4.5,10.5,7.5, PROP_ID=’K-11.4’/
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QUANTITY=’SPRINKLER LINK TEMPERATURE’,
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=7.5,10.5,7.5, PROP_ID=’K-11.4’/
```

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RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
```

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SPRAY_ANGLE=5.,80./
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QUANTITY='SPRINKLER LINK TEMPERATURE',
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID='water drops',
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID='sprinkler_upright',
SPRAY_ANGLE=5.,80./
&DEVC ID='Spr_60', XYZ=1.5,13.5,7.5, PROP_ID='K-11.4'/
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QUANTITY='SPRINKLER LINK TEMPERATURE',
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID='water drops',
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID='sprinkler_upright',
SPRAY_ANGLE=5.,80./
&DEVC ID='Spr_60', XYZ=4.5,13.5,7.5, PROP_ID='K-11.4'/
```

```
&PART ID='water drops', SPEC_ID='WATER VAPOR',DIAMETER=1000., /
&PROP ID='K-11.4',
QUANTITY='SPRINKLER LINK TEMPERATURE',
RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID='water drops',
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID='sprinkler_upright',
SPRAY_ANGLE=5.,80./
&DEVC ID='Spr_60', XYZ=7.5,13.5,7.5, PROP_ID='K-11.4'/
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&PART ID='water drops', SPEC_ID='WATER VAPOR',DIAMETER=1000., /
&PROP ID='K-11.4',
QUANTITY='SPRINKLER LINK TEMPERATURE',
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RTI=148,
C_FACTOR=0.7,
ACTIVATION_TEMPERATURE=74.,
PART_ID=’water drops’,
K_FACTOR=164.2,
OPERATING_PRESSURE=1.31,
PARTICLE_VELOCITY=8.01,
SMOKEVIEW_ID=’sprinkler_upright’,
SPRAY_ANGLE=5.,80./
&DEVC ID=’Spr_60’, XYZ=10.5,13.5,7.5, PROP_ID=’K-11.4’/
```

MEASURES

TEMPERATURE

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&DEVC XYZ=4.5,1.5,7.5, QUANTITY=’TEMPERATURE’, ID=’80’/
&DEVC XYZ=7.5,1.5,7.5, QUANTITY=’TEMPERATURE’, ID=’77’/
&DEVC XYZ=10.5,1.5,7.5, QUANTITY=’TEMPERATURE’, ID=’74’/
&DEVC XYZ=1.5,4.5,7.5, QUANTITY=’TEMPERATURE’, ID=’62’/
&DEVC XYZ=4.5,4.5,7.5, QUANTITY=’TEMPERATURE’, ID=’58’/
&DEVC XYZ=7.5,4.5,7.5, QUANTITY=’TEMPERATURE’, ID=’54’/
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&DEVC XYZ=1.5,7.5,7.5, QUANTITY=’TEMPERATURE’, ID=’63’/
&DEVC XYZ=4.5,7.5,7.5, QUANTITY=’TEMPERATURE’, ID=’59’/
&DEVC XYZ=7.5,7.5,7.5, QUANTITY=’TEMPERATURE’, ID=’55’/
&DEVC XYZ=10.5,7.5,7.5, QUANTITY=’TEMPERATURE’, ID=’51’/
&DEVC XYZ=1.5,10.5,7.5, QUANTITY=’TEMPERATURE’, ID=’64’/
&DEVC XYZ=4.5,10.5,7.5, QUANTITY=’TEMPERATURE’, ID=’60’/
&DEVC XYZ=7.5,10.5,7.5, QUANTITY=’TEMPERATURE’, ID=’56’/
&DEVC XYZ=10.5,10.5,7.5, QUANTITY=’TEMPERATURE’, ID=’52’/
&DEVC XYZ=1.5,13.5,7.5, QUANTITY=’TEMPERATURE’, ID=’65’/
&DEVC XYZ=4.5,13.5,7.5, QUANTITY=’TEMPERATURE’, ID=’61’/
&DEVC XYZ=7.5,13.5,7.5, QUANTITY=’TEMPERATURE’, ID=’57’/
&DEVC XYZ=10.5,13.5,7.5, QUANTITY=’TEMPERATURE’, ID=’53’/
&DEVC XYZ=6.0,8.1,7.5, QUANTITY=’TEMPERATURE’, ID=’49’/
&DEVC XYZ=6.0,8.4,7.5, QUANTITY=’TEMPERATURE’, ID=’48’/
&DEVC XYZ=6.0,8.7,7.5, QUANTITY=’TEMPERATURE’, ID=’47’/
&DEVC XYZ=6.0,9.0,7.5, QUANTITY=’TEMPERATURE’, ID=’46’/
&DEVC XYZ=6.0,9.3,7.5, QUANTITY=’TEMPERATURE’, ID=’45’/
&DEVC XYZ=6.0,9.6,7.5, QUANTITY=’TEMPERATURE’, ID=’44’/
&DEVC XYZ=6.0,9.9,7.5, QUANTITY=’TEMPERATURE’, ID=’43’/
```

MASS FLOW

```
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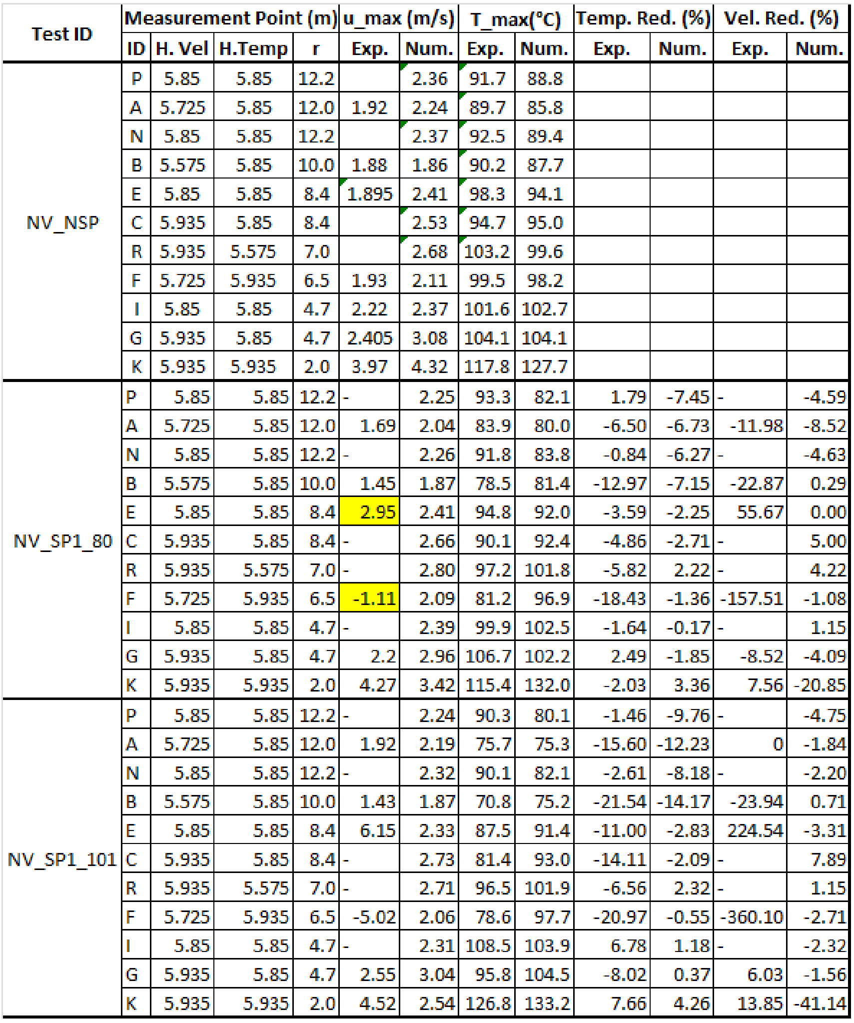
SLIDES

```
———————————————————————————-
&SLCF PBX=6.0, QUANTITY='TEMPERATURE', ID='TEMP VENT'/
&SLCF PBX=6.0, QUANTITY='U-VELOCITY', ID='VEL VENT'/
&SLCF PBZ=7.9, QUANTITY='W-VELOCITY', ID='VER VENT'/
&SLCF PBZ=7.9, QUANTITY='TEMPERATURE', ID='TEMP VENT CEIL'/
&SLCF PBZ=7.4, QUANTITY='TEMPERATURE', ID='TEMP CEILING'/
&SLCF PBY=9.0, QUANTITY='TEMPERATURE', ID='TEMP VENT Y'/
&SLCF PBY=9.0, QUANTITY='U-VELOCITY', ID='VEL VENT Y'/
———————————————————————————-
&TAIL/
```

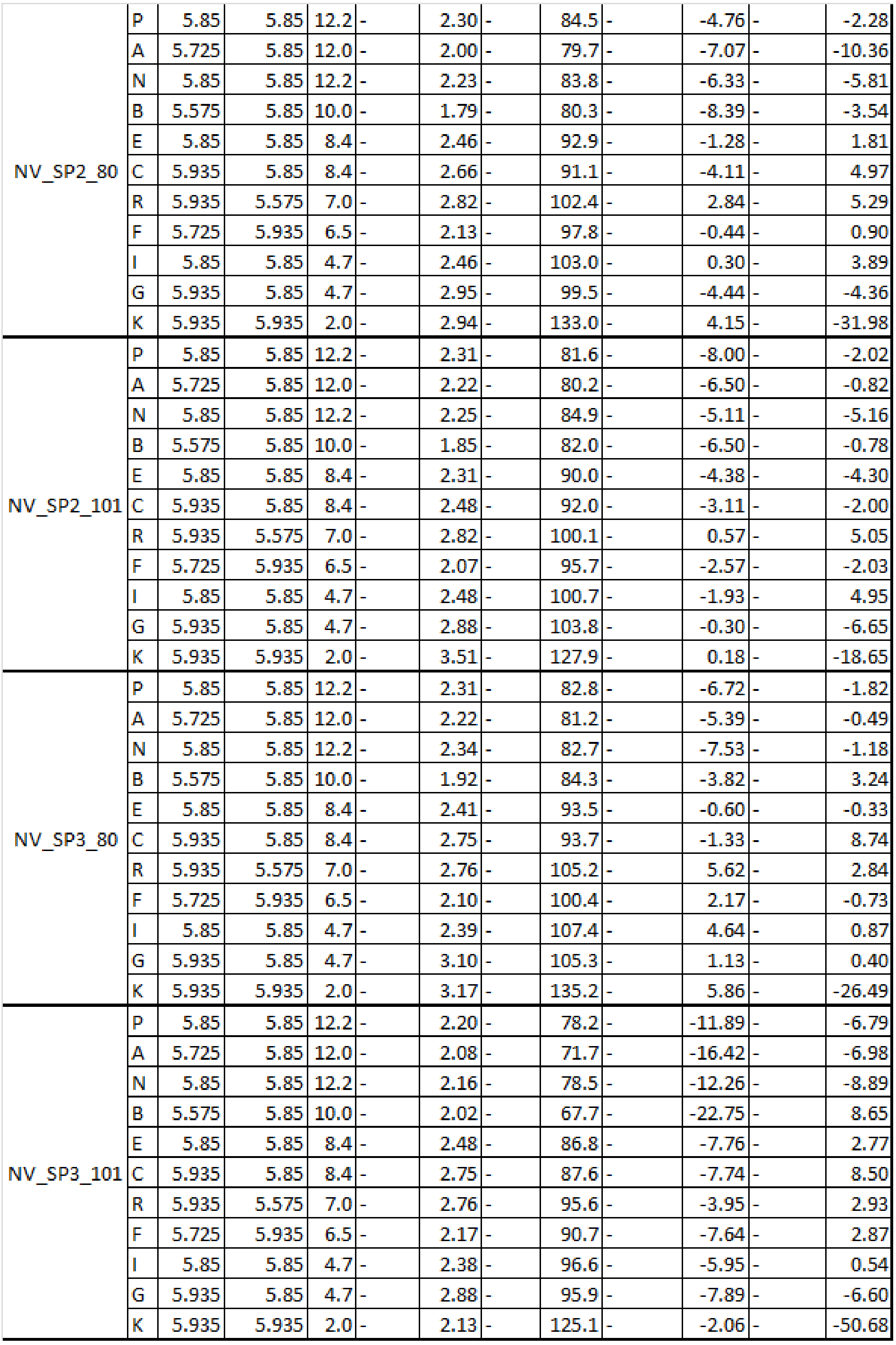
Appendix D

Experiment-Model Relation Data

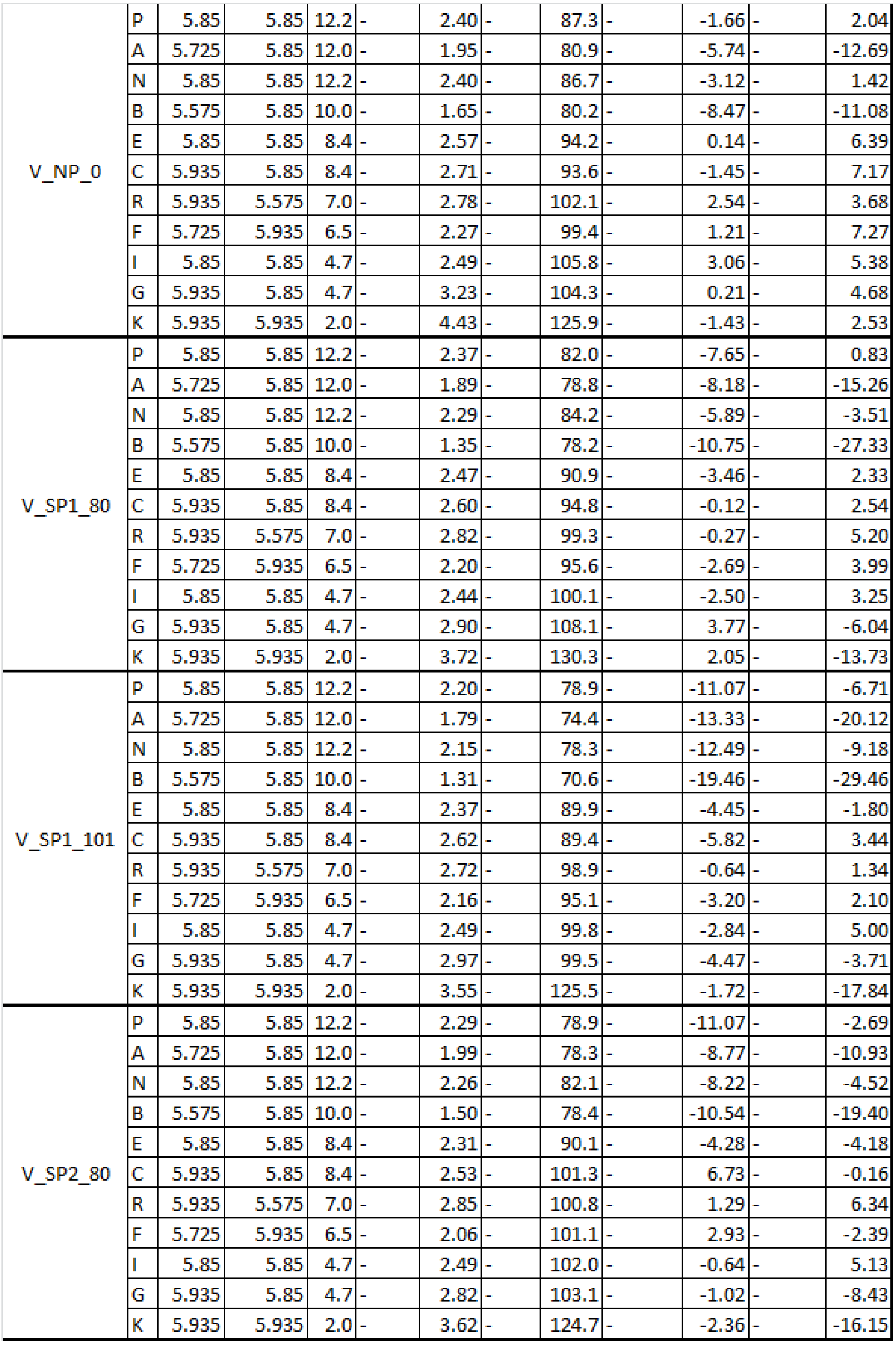
In the following tables temperature and velocity relations between experimental and simulated values are presented. The first column shows the test ID. Second column, *Measurement Point*, shows the location of the measurement point and the height where velocity and temperature were taken to calculate the relation. *u_max* and *T_max* are the maximum velocity and temperature values at each point. The last columns show the reduction or increase of each location according to equation 4.2. An error was reported for velocity data at locations E and F in the test NV_SP1_80-101 leading to very high numbers. These are not taken into account on the analysis.



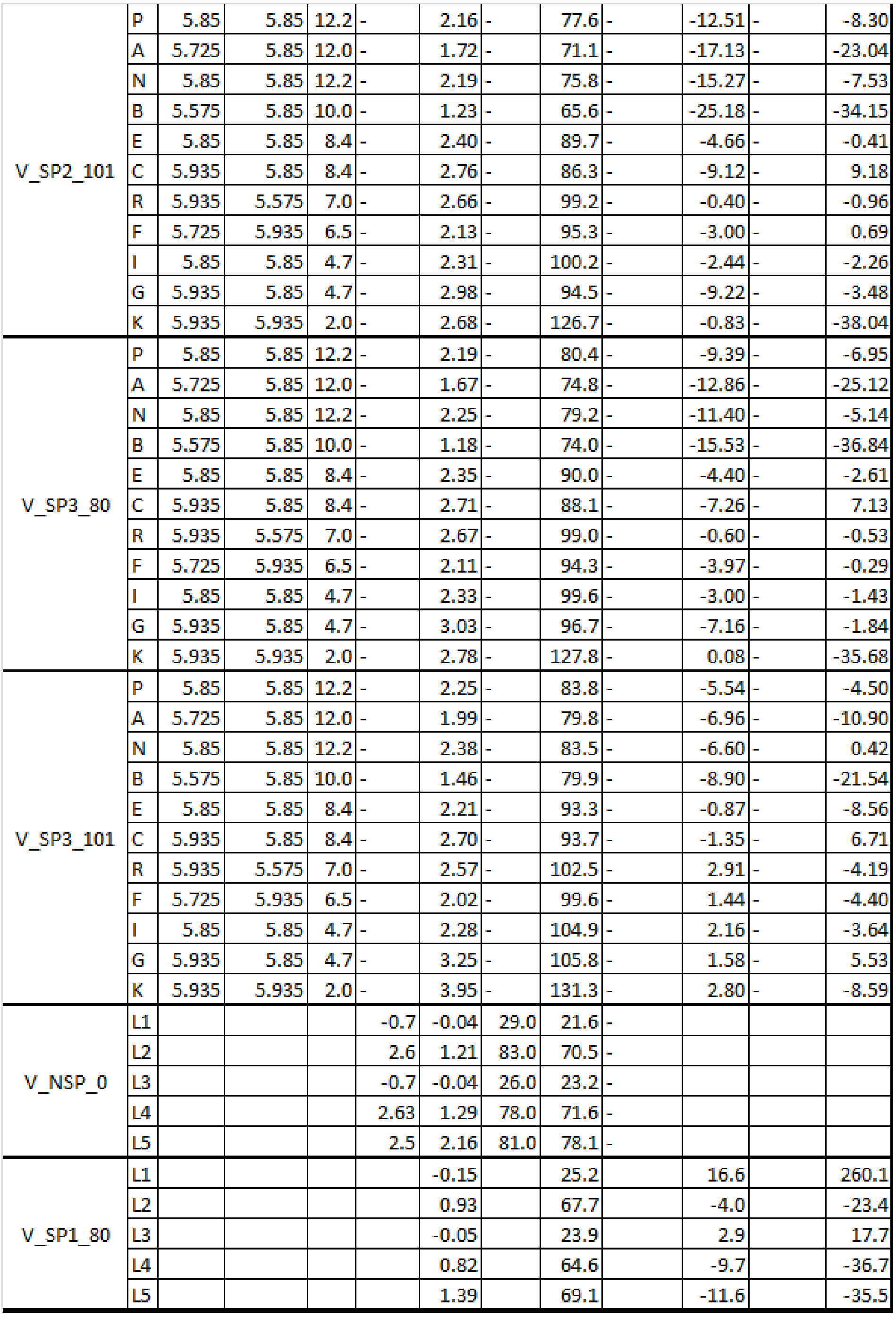
Test ID	Measurement Point (m)				u_max (m/s)		T_max(°C)		Temp. Red. (%)		Vel. Red. (%)	
	ID	H. Vel	H.Temp	r	Exp.	Num.	Exp.	Num.	Exp.	Num.	Exp.	Num.
NV_NSP	P	5.85	5.85	12.2		2.36	91.7	88.8				
	A	5.725	5.85	12.0	1.92	2.24	89.7	85.8				
	N	5.85	5.85	12.2		2.37	92.5	89.4				
	B	5.575	5.85	10.0	1.88	1.86	90.2	87.7				
	E	5.85	5.85	8.4	1.895	2.41	98.3	94.1				
	C	5.935	5.85	8.4		2.53	94.7	95.0				
	R	5.935	5.575	7.0		2.68	103.2	99.6				
	F	5.725	5.935	6.5	1.93	2.11	99.5	98.2				
	I	5.85	5.85	4.7	2.22	2.37	101.6	102.7				
	G	5.935	5.85	4.7	2.405	3.08	104.1	104.1				
	K	5.935	5.935	2.0	3.97	4.32	117.8	127.7				
NV_SP1_80	P	5.85	5.85	12.2	-	2.25	93.3	82.1	1.79	-7.45	-	-4.59
	A	5.725	5.85	12.0	1.69	2.04	83.9	80.0	-6.50	-6.73	-11.98	-8.52
	N	5.85	5.85	12.2	-	2.26	91.8	83.8	-0.84	-6.27	-	-4.63
	B	5.575	5.85	10.0	1.45	1.87	78.5	81.4	-12.97	-7.15	-22.87	0.29
	E	5.85	5.85	8.4	2.95	2.41	94.8	92.0	-3.59	-2.25	55.67	0.00
	C	5.935	5.85	8.4	-	2.66	90.1	92.4	-4.86	-2.71	-	5.00
	R	5.935	5.575	7.0	-	2.80	97.2	101.8	-5.82	2.22	-	4.22
	F	5.725	5.935	6.5	-1.11	2.09	81.2	96.9	-18.43	-1.36	-157.51	-1.08
	I	5.85	5.85	4.7	-	2.39	99.9	102.5	-1.64	-0.17	-	1.15
	G	5.935	5.85	4.7	2.2	2.96	106.7	102.2	2.49	-1.85	-8.52	-4.09
	K	5.935	5.935	2.0	4.27	3.42	115.4	132.0	-2.03	3.36	7.56	-20.85
NV_SP1_101	P	5.85	5.85	12.2	-	2.24	90.3	80.1	-1.46	-9.76	-	-4.75
	A	5.725	5.85	12.0	1.92	2.19	75.7	75.3	-15.60	-12.23	0	-1.84
	N	5.85	5.85	12.2	-	2.32	90.1	82.1	-2.61	-8.18	-	-2.20
	B	5.575	5.85	10.0	1.43	1.87	70.8	75.2	-21.54	-14.17	-23.94	0.71
	E	5.85	5.85	8.4	6.15	2.33	87.5	91.4	-11.00	-2.83	224.54	-3.31
	C	5.935	5.85	8.4	-	2.73	81.4	93.0	-14.11	-2.09	-	7.89
	R	5.935	5.575	7.0	-	2.71	96.5	101.9	-6.56	2.32	-	1.15
	F	5.725	5.935	6.5	-5.02	2.06	78.6	97.7	-20.97	-0.55	-360.10	-2.71
	I	5.85	5.85	4.7	-	2.31	108.5	103.9	6.78	1.18	-	-2.32
	G	5.935	5.85	4.7	2.55	3.04	95.8	104.5	-8.02	0.37	6.03	-1.56
	K	5.935	5.935	2.0	4.52	2.54	126.8	133.2	7.66	4.26	13.85	-41.14



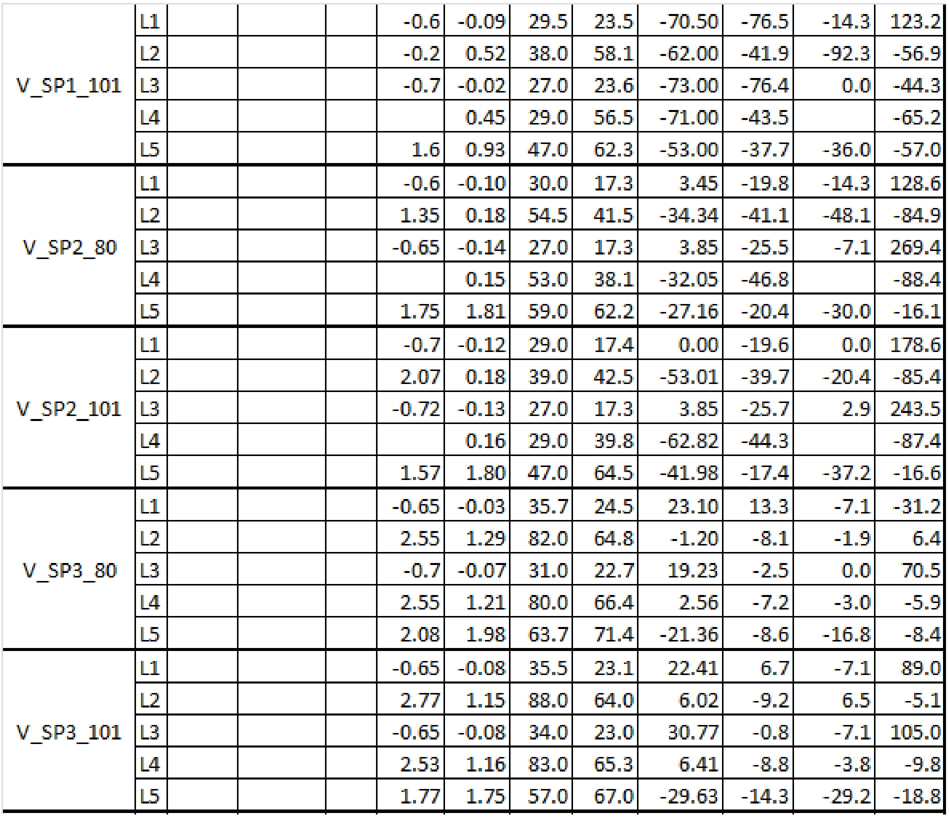
NV_SP2_80	P	5.85	5.85	12.2	-	2.30	-	84.5	-	-4.76	-	-2.28
	A	5.725	5.85	12.0	-	2.00	-	79.7	-	-7.07	-	-10.36
	N	5.85	5.85	12.2	-	2.23	-	83.8	-	-6.33	-	-5.81
	B	5.575	5.85	10.0	-	1.79	-	80.3	-	-8.39	-	-3.54
	E	5.85	5.85	8.4	-	2.46	-	92.9	-	-1.28	-	1.81
	C	5.935	5.85	8.4	-	2.66	-	91.1	-	-4.11	-	4.97
	R	5.935	5.575	7.0	-	2.82	-	102.4	-	2.84	-	5.29
	F	5.725	5.935	6.5	-	2.13	-	97.8	-	-0.44	-	0.90
	I	5.85	5.85	4.7	-	2.46	-	103.0	-	0.30	-	3.89
	G	5.935	5.85	4.7	-	2.95	-	99.5	-	-4.44	-	-4.36
	K	5.935	5.935	2.0	-	2.94	-	133.0	-	4.15	-	-31.98
NV_SP2_101	P	5.85	5.85	12.2	-	2.31	-	81.6	-	-8.00	-	-2.02
	A	5.725	5.85	12.0	-	2.22	-	80.2	-	-6.50	-	-0.82
	N	5.85	5.85	12.2	-	2.25	-	84.9	-	-5.11	-	-5.16
	B	5.575	5.85	10.0	-	1.85	-	82.0	-	-6.50	-	-0.78
	E	5.85	5.85	8.4	-	2.31	-	90.0	-	-4.38	-	-4.30
	C	5.935	5.85	8.4	-	2.48	-	92.0	-	-3.11	-	-2.00
	R	5.935	5.575	7.0	-	2.82	-	100.1	-	0.57	-	5.05
	F	5.725	5.935	6.5	-	2.07	-	95.7	-	-2.57	-	-2.03
	I	5.85	5.85	4.7	-	2.48	-	100.7	-	-1.93	-	4.95
	G	5.935	5.85	4.7	-	2.88	-	103.8	-	-0.30	-	-6.65
	K	5.935	5.935	2.0	-	3.51	-	127.9	-	0.18	-	-18.65
NV_SP3_80	P	5.85	5.85	12.2	-	2.31	-	82.8	-	-6.72	-	-1.82
	A	5.725	5.85	12.0	-	2.22	-	81.2	-	-5.39	-	-0.49
	N	5.85	5.85	12.2	-	2.34	-	82.7	-	-7.53	-	-1.18
	B	5.575	5.85	10.0	-	1.92	-	84.3	-	-3.82	-	3.24
	E	5.85	5.85	8.4	-	2.41	-	93.5	-	-0.60	-	-0.33
	C	5.935	5.85	8.4	-	2.75	-	93.7	-	-1.33	-	8.74
	R	5.935	5.575	7.0	-	2.76	-	105.2	-	5.62	-	2.84
	F	5.725	5.935	6.5	-	2.10	-	100.4	-	2.17	-	-0.73
	I	5.85	5.85	4.7	-	2.39	-	107.4	-	4.64	-	0.87
	G	5.935	5.85	4.7	-	3.10	-	105.3	-	1.13	-	0.40
	K	5.935	5.935	2.0	-	3.17	-	135.2	-	5.86	-	-26.49
NV_SP3_101	P	5.85	5.85	12.2	-	2.20	-	78.2	-	-11.89	-	-6.79
	A	5.725	5.85	12.0	-	2.08	-	71.7	-	-16.42	-	-6.98
	N	5.85	5.85	12.2	-	2.16	-	78.5	-	-12.26	-	-8.89
	B	5.575	5.85	10.0	-	2.02	-	67.7	-	-22.75	-	8.65
	E	5.85	5.85	8.4	-	2.48	-	86.8	-	-7.76	-	2.77
	C	5.935	5.85	8.4	-	2.75	-	87.6	-	-7.74	-	8.50
	R	5.935	5.575	7.0	-	2.76	-	95.6	-	-3.95	-	2.93
	F	5.725	5.935	6.5	-	2.17	-	90.7	-	-7.64	-	2.87
	I	5.85	5.85	4.7	-	2.38	-	96.6	-	-5.95	-	0.54
	G	5.935	5.85	4.7	-	2.88	-	95.9	-	-7.89	-	-6.60
	K	5.935	5.935	2.0	-	2.13	-	125.1	-	-2.06	-	-50.68



V_NP_0	P	5.85	5.85	12.2	-	2.40	-	87.3	-	-1.66	-	2.04
	A	5.725	5.85	12.0	-	1.95	-	80.9	-	-5.74	-	-12.69
	N	5.85	5.85	12.2	-	2.40	-	86.7	-	-3.12	-	1.42
	B	5.575	5.85	10.0	-	1.65	-	80.2	-	-8.47	-	-11.08
	E	5.85	5.85	8.4	-	2.57	-	94.2	-	0.14	-	6.39
	C	5.935	5.85	8.4	-	2.71	-	93.6	-	-1.45	-	7.17
	R	5.935	5.575	7.0	-	2.78	-	102.1	-	2.54	-	3.68
	F	5.725	5.935	6.5	-	2.27	-	99.4	-	1.21	-	7.27
	I	5.85	5.85	4.7	-	2.49	-	105.8	-	3.06	-	5.38
	G	5.935	5.85	4.7	-	3.23	-	104.3	-	0.21	-	4.68
	K	5.935	5.935	2.0	-	4.43	-	125.9	-	-1.43	-	2.53
V_SP1_80	P	5.85	5.85	12.2	-	2.37	-	82.0	-	-7.65	-	0.83
	A	5.725	5.85	12.0	-	1.89	-	78.8	-	-8.18	-	-15.26
	N	5.85	5.85	12.2	-	2.29	-	84.2	-	-5.89	-	-3.51
	B	5.575	5.85	10.0	-	1.35	-	78.2	-	-10.75	-	-27.33
	E	5.85	5.85	8.4	-	2.47	-	90.9	-	-3.46	-	2.33
	C	5.935	5.85	8.4	-	2.60	-	94.8	-	-0.12	-	2.54
	R	5.935	5.575	7.0	-	2.82	-	99.3	-	-0.27	-	5.20
	F	5.725	5.935	6.5	-	2.20	-	95.6	-	-2.69	-	3.99
	I	5.85	5.85	4.7	-	2.44	-	100.1	-	-2.50	-	3.25
	G	5.935	5.85	4.7	-	2.90	-	108.1	-	3.77	-	-6.04
	K	5.935	5.935	2.0	-	3.72	-	130.3	-	2.05	-	-13.73
V_SP1_101	P	5.85	5.85	12.2	-	2.20	-	78.9	-	-11.07	-	-6.71
	A	5.725	5.85	12.0	-	1.79	-	74.4	-	-13.33	-	-20.12
	N	5.85	5.85	12.2	-	2.15	-	78.3	-	-12.49	-	-9.18
	B	5.575	5.85	10.0	-	1.31	-	70.6	-	-19.46	-	-29.46
	E	5.85	5.85	8.4	-	2.37	-	89.9	-	-4.45	-	-1.80
	C	5.935	5.85	8.4	-	2.62	-	89.4	-	-5.82	-	3.44
	R	5.935	5.575	7.0	-	2.72	-	98.9	-	-0.64	-	1.34
	F	5.725	5.935	6.5	-	2.16	-	95.1	-	-3.20	-	2.10
	I	5.85	5.85	4.7	-	2.49	-	99.8	-	-2.84	-	5.00
	G	5.935	5.85	4.7	-	2.97	-	99.5	-	-4.47	-	-3.71
	K	5.935	5.935	2.0	-	3.55	-	125.5	-	-1.72	-	-17.84
V_SP2_80	P	5.85	5.85	12.2	-	2.29	-	78.9	-	-11.07	-	-2.69
	A	5.725	5.85	12.0	-	1.99	-	78.3	-	-8.77	-	-10.93
	N	5.85	5.85	12.2	-	2.26	-	82.1	-	-8.22	-	-4.52
	B	5.575	5.85	10.0	-	1.50	-	78.4	-	-10.54	-	-19.40
	E	5.85	5.85	8.4	-	2.31	-	90.1	-	-4.28	-	-4.18
	C	5.935	5.85	8.4	-	2.53	-	101.3	-	6.73	-	-0.16
	R	5.935	5.575	7.0	-	2.85	-	100.8	-	1.29	-	6.34
	F	5.725	5.935	6.5	-	2.06	-	101.1	-	2.93	-	-2.39
	I	5.85	5.85	4.7	-	2.49	-	102.0	-	-0.64	-	5.13
	G	5.935	5.85	4.7	-	2.82	-	103.1	-	-1.02	-	-8.43
	K	5.935	5.935	2.0	-	3.62	-	124.7	-	-2.36	-	-16.15



V_SP2_101	P	5.85	5.85	12.2	-	2.16	-	77.6	-	-12.51	-	-8.30
	A	5.725	5.85	12.0	-	1.72	-	71.1	-	-17.13	-	-23.04
	N	5.85	5.85	12.2	-	2.19	-	75.8	-	-15.27	-	-7.53
	B	5.575	5.85	10.0	-	1.23	-	65.6	-	-25.18	-	-34.15
	E	5.85	5.85	8.4	-	2.40	-	89.7	-	-4.66	-	-0.41
	C	5.935	5.85	8.4	-	2.76	-	86.3	-	-9.12	-	9.18
	R	5.935	5.575	7.0	-	2.66	-	99.2	-	-0.40	-	-0.96
	F	5.725	5.935	6.5	-	2.13	-	95.3	-	-3.00	-	0.69
	I	5.85	5.85	4.7	-	2.31	-	100.2	-	-2.44	-	-2.26
	G	5.935	5.85	4.7	-	2.98	-	94.5	-	-9.22	-	-3.48
	K	5.935	5.935	2.0	-	2.68	-	126.7	-	-0.83	-	-38.04
V_SP3_80	P	5.85	5.85	12.2	-	2.19	-	80.4	-	-9.39	-	-6.95
	A	5.725	5.85	12.0	-	1.67	-	74.8	-	-12.86	-	-25.12
	N	5.85	5.85	12.2	-	2.25	-	79.2	-	-11.40	-	-5.14
	B	5.575	5.85	10.0	-	1.18	-	74.0	-	-15.53	-	-36.84
	E	5.85	5.85	8.4	-	2.35	-	90.0	-	-4.40	-	-2.61
	C	5.935	5.85	8.4	-	2.71	-	88.1	-	-7.26	-	7.13
	R	5.935	5.575	7.0	-	2.67	-	99.0	-	-0.60	-	-0.53
	F	5.725	5.935	6.5	-	2.11	-	94.3	-	-3.97	-	-0.29
	I	5.85	5.85	4.7	-	2.33	-	99.6	-	-3.00	-	-1.43
	G	5.935	5.85	4.7	-	3.03	-	96.7	-	-7.16	-	-1.84
	K	5.935	5.935	2.0	-	2.78	-	127.8	-	0.08	-	-35.68
V_SP3_101	P	5.85	5.85	12.2	-	2.25	-	83.8	-	-5.54	-	-4.50
	A	5.725	5.85	12.0	-	1.99	-	79.8	-	-6.96	-	-10.90
	N	5.85	5.85	12.2	-	2.38	-	83.5	-	-6.60	-	0.42
	B	5.575	5.85	10.0	-	1.46	-	79.9	-	-8.90	-	-21.54
	E	5.85	5.85	8.4	-	2.21	-	93.3	-	-0.87	-	-8.56
	C	5.935	5.85	8.4	-	2.70	-	93.7	-	-1.35	-	6.71
	R	5.935	5.575	7.0	-	2.57	-	102.5	-	2.91	-	-4.19
	F	5.725	5.935	6.5	-	2.02	-	99.6	-	1.44	-	-4.40
	I	5.85	5.85	4.7	-	2.28	-	104.9	-	2.16	-	-3.64
	G	5.935	5.85	4.7	-	3.25	-	105.8	-	1.58	-	5.53
	K	5.935	5.935	2.0	-	3.95	-	131.3	-	2.80	-	-8.59
V_NSP_0	L1				-0.7	-0.04	29.0	21.6	-			
	L2				2.6	1.21	83.0	70.5	-			
	L3				-0.7	-0.04	26.0	23.2	-			
	L4				2.63	1.29	78.0	71.6	-			
	L5				2.5	2.16	81.0	78.1	-			
V_SP1_80	L1					-0.15		25.2		16.6		260.1
	L2					0.93		67.7		-4.0		-23.4
	L3					-0.05		23.9		2.9		17.7
	L4					0.82		64.6		-9.7		-36.7
	L5					1.39		69.1		-11.6		-35.5



V_SP1_101	L1				-0.6	-0.09	29.5	23.5	-70.50	-76.5	-14.3	123.2
	L2				-0.2	0.52	38.0	58.1	-62.00	-41.9	-92.3	-56.9
	L3				-0.7	-0.02	27.0	23.6	-73.00	-76.4	0.0	-44.3
	L4					0.45	29.0	56.5	-71.00	-43.5		-65.2
	L5				1.6	0.93	47.0	62.3	-53.00	-37.7	-36.0	-57.0
V_SP2_80	L1				-0.6	-0.10	30.0	17.3	3.45	-19.8	-14.3	128.6
	L2				1.35	0.18	54.5	41.5	-34.34	-41.1	-48.1	-84.9
	L3				-0.65	-0.14	27.0	17.3	3.85	-25.5	-7.1	269.4
	L4					0.15	53.0	38.1	-32.05	-46.8		-88.4
	L5				1.75	1.81	59.0	62.2	-27.16	-20.4	-30.0	-16.1
V_SP2_101	L1				-0.7	-0.12	29.0	17.4	0.00	-19.6	0.0	178.6
	L2				2.07	0.18	39.0	42.5	-53.01	-39.7	-20.4	-85.4
	L3				-0.72	-0.13	27.0	17.3	3.85	-25.7	2.9	243.5
	L4					0.16	29.0	39.8	-62.82	-44.3		-87.4
	L5				1.57	1.80	47.0	64.5	-41.98	-17.4	-37.2	-16.6
V_SP3_80	L1				-0.65	-0.03	35.7	24.5	23.10	13.3	-7.1	-31.2
	L2				2.55	1.29	82.0	64.8	-1.20	-8.1	-1.9	6.4
	L3				-0.7	-0.07	31.0	22.7	19.23	-2.5	0.0	70.5
	L4				2.55	1.21	80.0	66.4	2.56	-7.2	-3.0	-5.9
	L5				2.08	1.98	63.7	71.4	-21.36	-8.6	-16.8	-8.4
V_SP3_101	L1				-0.65	-0.08	35.5	23.1	22.41	6.7	-7.1	89.0
	L2				2.77	1.15	88.0	64.0	6.02	-9.2	6.5	-5.1
	L3				-0.65	-0.08	34.0	23.0	30.77	-0.8	-7.1	105.0
	L4				2.53	1.16	83.0	65.3	6.41	-8.8	-3.8	-9.8
	L5				1.77	1.75	57.0	67.0	-29.63	-14.3	-29.2	-18.8