

# Enhancing Fire Detection Capabilities in Carbon Storage Facilities Using Fire Dynamics Simulator

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**Abstract:** Carbon storage facilities are essential in carbon sequestration and mitigation of climate change but the storage of carbonaceous substances brings with them high risk of fire occurrences in the form of smoldering combustion, spontaneous ignition and explosions of combustible dusts. The traditional fire detectors usually are not able to give early alerts because the smoke takes time to develop and the ventilation in storage facilities is complicated. The paper describes the improved fire detection system of carbon storage facilities based on Fire Dynamics Simulator (FDS). The simulations are carried out using computational fluid dynamics where the growth of the fire, propagation of smoke, temperature and the evolution of the gas species are analyzed under different fire conditions. The detector response behavior is tested by combining multi-sensor models, which consist of smoke, heat, and gas sensors to determine the best sensor placement and detection threshold. The outcome of the simulations indicate that using gas based and multi sensor detection schemes would save a great deal of time, relative to the conventional smoke only systems in terms of detection time. The suggested solution offers a performance-based model of efficient and reliable fire detection systems design in carbon storage processes.

**Keywords:** Fire Dynamics Simulator (FDS), Carbon Storage, Fire Detection Systems, Computational Fluid Dynamics (CFD), Multi-Sensor Detection, Combustible Dust Fire

## I. INTRODUCTION

Carbon storage plants have become very prominent in the past few years because of their contribution in the processes of carbon sequestration, industrial processing and mitigation of climatic changes. The carbonaceous substances that are usually stored in these facilities include biochar, activated carbons, carbon black and other forms of solid carbon. Although such materials are advantageous in environmental and industrial uses, they are quite risky in terms of fire and explosions due to the large surface area, porosity and oxidation tendency under desirable thermal and environmental conditions [14], [18], [21].

Carbon storage fires tend to develop as smoldering combustion and not open flaming fires. Low heat release rate, slow propagation, and minimal visible smoke characterize smoldering combustion, whereas producing dangerous gases, such as carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) at the initial stages [15], [16]. This has made the traditional fire detection systems which are based mainly on sensing smoke or heat often slow to alert or they fail to notice the incipient fire conditions, thereby enhancing the probability of fire spread, loss of materials and personnel safety risks.

Recent development of technologies in fire detection such as image-based and intelligent detection systems has proved to be better in the conventional building environment [1]. Nonetheless, in carbon storage plants, they are limited in their applicability because of low visibility due to dust cover, complicated geometries of the enclosures, variable and changing conditions of ventilation, and prevailing smoldering fire behavior. These difficulties indicate why performance-based fire safety engineering methods should be specific to the carbon-rich storage settings.

The identification of fire in these facilities requires more than one parameter of sensing because it involves numerous physical and chemical indicators. Strictly speaking, initial combustion in the carbon store may be better defined as a rise in gas production and slight alterations in temperature that are noticeable prior to the emergence of smoke. Table I

highlights the most important fire detection-related parameters that were taken into account in the current study and simulated with the help of Fire Dynamics Simulator (FDS).

Table I: Fire detection related parameters simulated using FDS

Parameter	What FDS Simulates
Temperature	Rise due to flames or heat release
Smoke concentration	Smoke movement and density
Gas concentrations (CO, CO <sub>2</sub> , O <sub>2</sub> )	Helps detect combustion gases
Visibility reduction	Affects optical detectors (e.g., beam sensors)
Heat flux	Helps assess response of thermal detectors
Flame spread and growth	Important for early warning systems

Computational Fluid Dynamics (CFD) has become a viable method of studying the behavior of fire, smoke, and gas dispersion under valid operating conditions. The Fire Dynamics Simulator (FDS) is an open-source tool that is broadly used to model fluid flow, heat transfer, combustion, and detector response caused by fire in enclosed and semi-enclosed environments [3], [7]. FDS has been widely tested on experimental and extensive fire studies showing its predictability in the dynamics of fires and smoke movement in the situation of an industrial and compartment fire [4], [5], [24].

A number of researches have used FDS to study localized fires, ventilation influences and thermal interactions in large enclosures [6], [25], [26]. Nevertheless, current literature is mainly dedicated to the development of fire, the spreading of smoke, and the methods of its extinguishment, but not to the detection of the fire at a very early stage of its development. Specifically, little attention has been paid to optimization of carbon storage facility fire detection systems whereby, the generation of gas is much earlier than the appearance of visible smoke and rise of heat. Besides, the combination of multi-sensor detection strategies, such as smoke, heat, and gas sensors, based on the CFD-based analysis is still not fully studied.

To overcome these drawbacks, this research has utilized an FDS-driven model to consider the fire progression and the reaction of detectors in the carbon storage fire conditions that are realistic. Fig. 1 shows the workflow of the whole process of simulation, analysis, and enhancement of detection procedure.

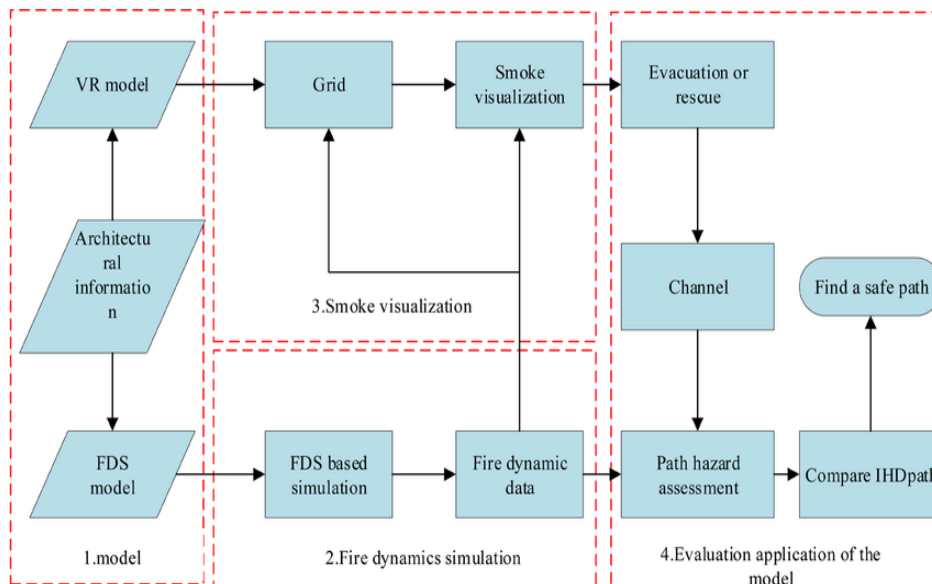


Fig. 1. Overall workflow for enhancing fire detection in carbon storage using FDS

Moreover, the design of fire detection systems in industrial use is required to conform to the set standards and codes of practice including the IS 15908 which highlights that the choice, installation, and maintenance of fire detection and alarm systems should be done properly [13]. Nevertheless, these standards only give partial information on how to optimize sensors and their detection capabilities in complex fire conditions as would occur in a carbon storage facility. It is based on these issues that this paper suggests a more efficient fire detection system on carbon storage plant by modeling through Fire Dynamics Simulator. This paper examines fire behavior, smoke dynamics, temperature variation

and evolution of the gas species during realistic fire conditions. The proposed method will enhance the early fire detection performance, sensor location optimization and the general performance of fire safety in the carbon storage scenario through a combination of CFD simulation outcomes and detector response analysis techniques.

## II. SYSTEM MODEL AND SIMULATION METHODOLOGY

### A. Carbon Storage Facility Layout

The study considers a typical carbon storage facility that contains bulk carbonaceous materials, including carbon black, activated carbon, and biochar. The facility plan also contains storage bins, access aisle, ventilation and fire detection sensors. Since stored carbon is porous and has a high surface area, the facility is susceptible to smoldering combustion, which will actually start in limited locations before spreading massively [15], [16]. Knowing the spatial set-up is important in ambient sensor location and in detection early alerts.

### B. Fire Dynamics Simulator (FDS) Overview

Like other computational fluid dynamics (CFD) models, Fire Dynamics Simulator (FDS) is a NIST tool created to perform simulations of fire-driven fluid flow, heat transfer and combustion [7], [10]. FDS is used to solve the NavierStokes equations in low-speed, thermally-driven flows as well as models smoke production, generation of gas species, and spread of flame. The program can simulate the response of detectors of smoke, heat, and gas sensors, thus it is capable of figuring out the fire-detecting performance in carbon storage settings [4], [5].

### C. Fire Scenario Definition

Simulated fire scenarios were determined to replicate both the smoldering and flaming situations in the facility. Input parameters include:

- Initial ambient temperature: 25°C
- Fuel properties: carbon density, porosity, heat release rate
- Ventilation rate: natural and forced airflow
- Ignition sources: localized hot spots or sparks

Such tests permit to estimate the increase of temperature, the amount of gas (CO, CO<sub>2</sub>) usages, the smoke density, and the decrease of visibility that are some essential signs used by the fire detection systems [14], [18], [21].

### D. CFD Modeling Parameters

Table II is a summary of major simulation parameters applied in FDS when modeling the dynamic of the fire in the carbon storage facility.

Table II: FDS Simulation Parameters for Carbon Storage Fire Scenarios

Parameter	Value/Range	Description
Grid size	0.2 m	Resolution of computational domain
Simulation duration	1800 s	Total simulation time for fire evolution
Fuel load	50–100 kg/m <sup>3</sup>	Carbon material density in storage bins
Heat release rate	150–400 kW	Representative for smoldering/flaming fires
Ventilation	0.1–1 m <sup>3</sup> /s	Natural and forced airflow conditions
Detector type	Smoke, Heat, Gas	Modeled sensor responses in FDS

### E. Sensor Modeling and Placement

The detectors of the FDS were to be modeled by the traditional optical smoke, heat, and gas sensor algorithms. The positioning was done to ensure it utilizes the earliest fire alarms with the least possible false alarms caused by dust or normal ventilation. The simulation took into consideration:

- Detector height relative to the floor
- Proximity to potential ignition points
- Influence of smoke stratification and airflow patterns

The workflow of fire detection simulation at the carbon storage facility is depicted in Fig. 2, which shows that the process is characterised by interaction between fire development, transport of smoke and gasses, and detectors.

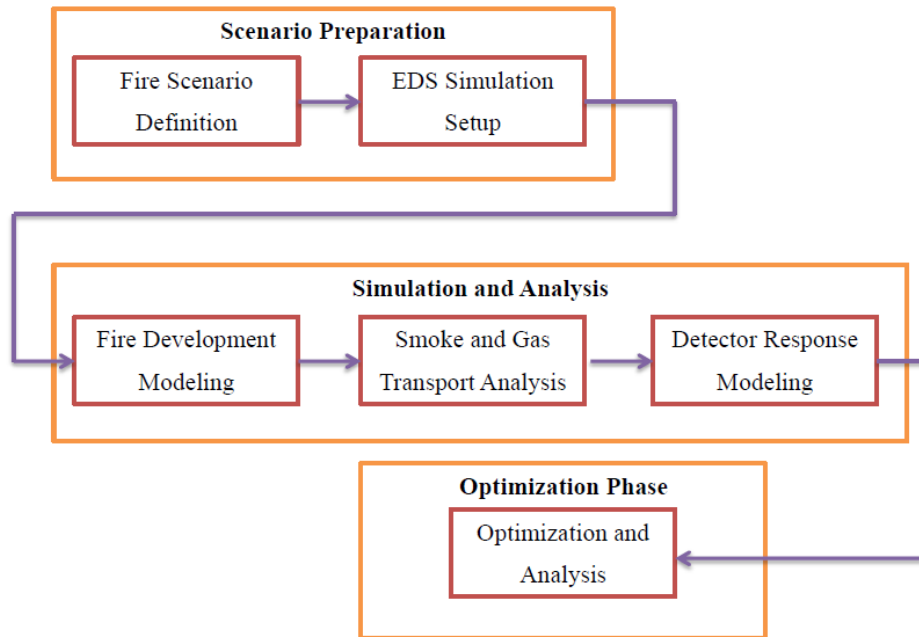


Fig. 2. Workflow of fire simulation and detector response modeling in FDS

### III. SIMULATION RESULTS AND DISCUSSION

#### A. Temperature Distribution and Flame Spread

FDS was employed to determine the temperature distribution in the carbon storage facility both in adiabatic and non-adiabatic conditions. Fig. 3. gives temperature contours and profiles through the reactor centerline. In the adiabatic case, the sustained temperatures (>1200 K) are higher across the domain, which favors the formation of carbon blacks at a higher rate. The non-adiabatic simulation exhibits relatively low temperatures because boundary losses of heat are experienced.

The comparison of the regular and refined meshes portrays that there are few differences in the predicted temperatures and this is confirmation that the computational grid selected gives a lot of accuracy with minimized computational efficiency.

Patterns of flame spread suggest that the smoldering fires move slowly at the onset, confined to local areas but those fires that spread flamingly are seen spreading rapidly along pathways of fuel-rich zones. These temperature patterns are very vital in computing the best detector location and enabling temperature.

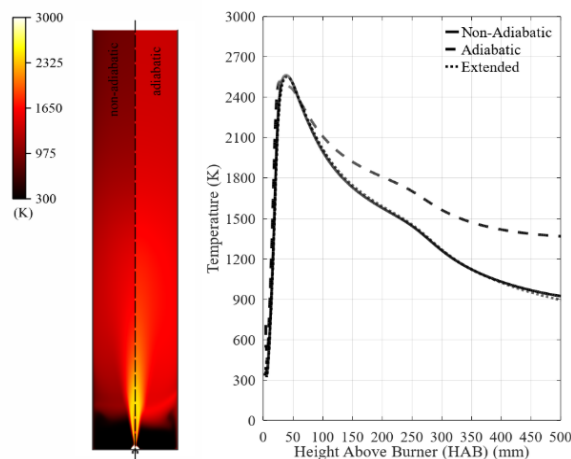


Fig. 3. Centerline temperature contours and profiles (adiabatic dotted and non-adiabatic solid) case.

**B. Smoke and Gas Concentration Analysis**

Smoke density and gas concentrations (CO, CO<sub>2</sub>) were tested with the use of FDS simulations throughout the storage facility.

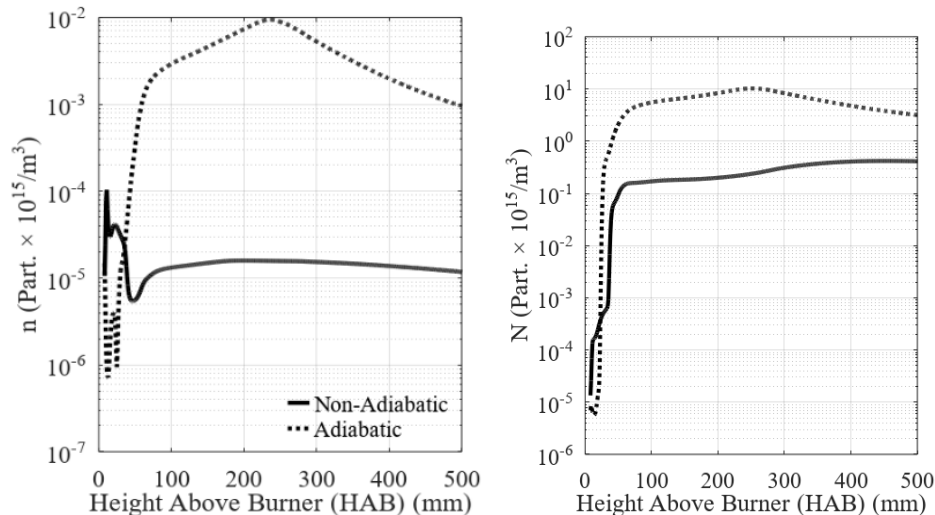


Fig. 4. Normalized nuclei concentration profile and normalized particle number concentration profile: non-adiabatic (solid line) and adiabatic (dotted line).

Fig. 4. the normalized concentration of the nuclei as well as the concentration of the particle number as a function of the height of the reactor. The rates of nucleation are found to increase in adiabatic conditions and therefore the level of carbon black particles also increases towards the lower part of the reactor.

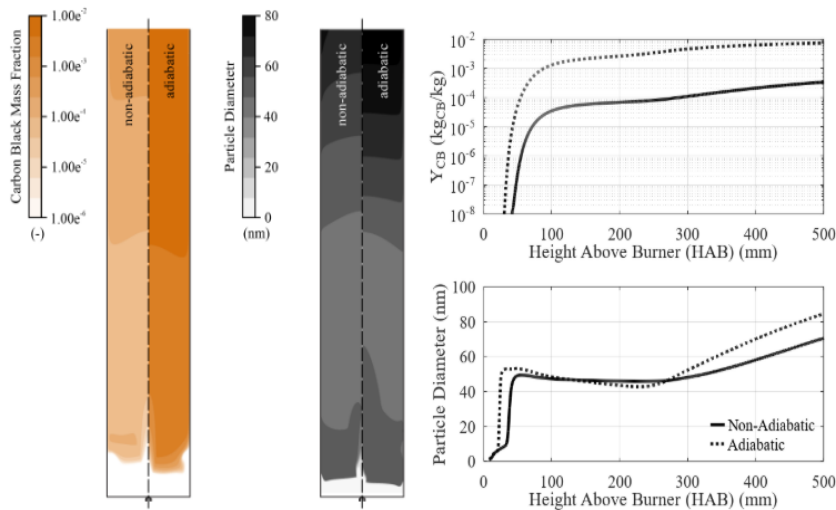


Fig. 5. Contours of carbon black mass fraction profile and particle diameter versus reactor height: non-adiabatic and adiabatic.

Fig. 5. indicates contours of carbon black mass fraction and profiles of particle diameter highlighting the fact that at higher temperatures the particle grows faster and in higher altitude it grows slowly because in the high altitude, the nucleation decreases rapidly.

These findings show that the gas emissions are at a very early stage before the visualization of smoke and therefore gas sensors are necessary to identify it at the right time when in carbon-contaminated storage facilities.

**C. Detector Response Analysis**

Smoke, heat and gas sensors response was tested through the application of the combination of multi-sensor models in FDS.

Low smoke density causes the smoke detectors to become inactive in the smoldering fire. Gas sensors (CO/CO<sub>2</sub>) give earlier signals of detection and therefore response time is much less. Multi-sensor detectors that combined the input of smoke, heat and gas showed the highest speed of detection and it is evident that a mixture of systems is beneficial.

Table III: Detector Activation Times for Different Fire Scenarios

Fire Scenario	Smoke Detector	Heat Detector	Gas Detector	Multi-Sensor Detector
Smoldering Fire	180 s	150 s	90 s	75 s
Flaming Fire	60 s	50 s	40 s	35 s



Fig. 5. Multi-sensor detector for smoldering and flaming fires

**D. Comparison of Smoldering vs Flaming Fires**

Smoldering fires: Minimal heat release, minimal smoke, low speed of propagation and premature gas release. Danger of invisible increase in case only smoke/heat detectors are employed.

Flaming fires: Rapid generation of heat and smoke; traditional sensors are more dependable to turn on. Simulation means that the carbon storage facilities should have sensors that can respond to the slightest temperature variations and even the formations of gaseous to enhance the level of safety and limit the fire damages.

**E. Early Detection Performance**

Optimal sensor location could be achieved by combining the CFD simulation outcomes with detector modeling. Key observations include:

Fires are noticed earlier in their origin by gas detecting sensors on the area instead of smoke detecting ones mounted on ceilings.

Multi-sensor detectors are also reliable during early warning during dust laden and ill-ventilated conditions. The CFD-based placement of sensors making sure that smoldering fires do not grow in mass enough poses potential damage minimizing and providing staff with the necessary safety.

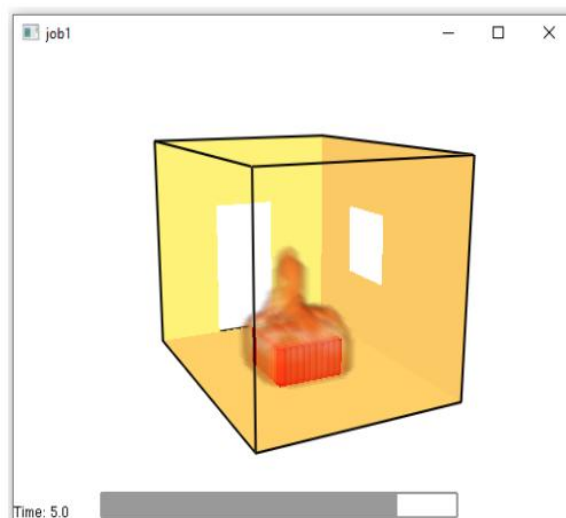


Fig. 6. Temperature, smoke, and gas distribution visualization in the carbon storage facility by Smoke View

#### IV. PROPOSED FIRE DETECTION SYSTEM AND IMPLEMENTATION

##### A. Existing Fire Detection and Firefighting Equipment

Existing fire safety provisions at the carbon storage facilities comprise chiefly of the fixed beam detectors, fire extinguishers as well as hydrants that are man operated and sprinkler systems that are water based. Large sections of area are monitored by optical beam detectors which emit beams and sound off alarm when their beam is disrupted (Fig. 7) and fire extinguishers and hydrants are used to provide manual control of local fires (Fig. 8). Water sprinklers are fully automated and keep flames down and restrict the spread of fire (Fig. 9). Regardless of their popularity, these systems possess certain drawbacks: optical beam detectors can be affected by dust and fail to be sensitive enough especially at the very early stage of smoldering combustion development, manual extinguishers and hydrants rely on human operator actions and might respond to it with lateness, and single-sensor detection systems will generally give late warnings in the earlier stages of smoldering combustion development.

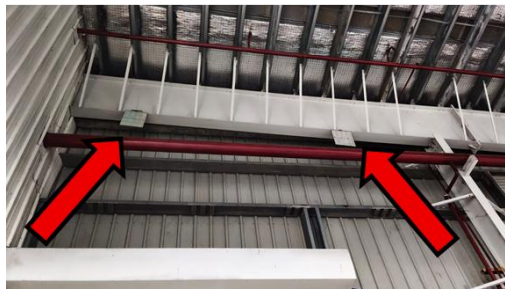


Fig. 7. Fixed beam detector for fire detection purpose



Fig. 8. Fire Extinguisher & Fire Hydrant for fire fighting

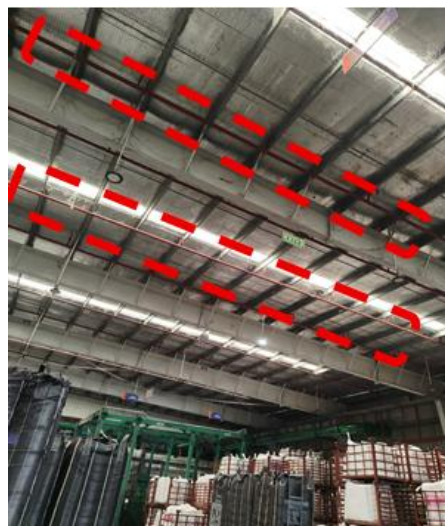


Fig. 9. Water sprinkler placed for fire fighting

**B. Proposed Fire Detection Implementation**

A multi-sensor detection method should be used to enhance the process of early detection in carbon storage facilities. This system combines smoke detectors, heat detectors and carbon monoxide (CO) detectors to overcome the special difficulties with carbon dust setting:

- Detects fires below the lower explosible dust limit (~50 g/m<sup>3</sup>).
- Provides early warning during smoldering fires before visible smoke develops.
- Reduces false alarms caused by dust or ventilation airflow.
- Optimized placement based on FDS simulation results of smoke, gas, and temperature distribution.

**C. Multi-Sensor Detector Features and Specifications**

Key Features:

- UL approved with dual LED lights that allow viewing of 360°.
- Polarity-free and can be installed simply with a low profile housing.
- Has 8-way DIP switches with support to 254 addressable devices.

Table IV: Electrical Specifications

Parameter	Value / Range	Description
Operating Voltage	17–28 V DC	Standard power supply
Reset Voltage	< 3 V	After alarm reset
Standby Current	500 μA	Low-power idle
Alarm Current	7 mA	Current during alarm
Smoke Sensitivity	1.1–2.3 %/ft	Adjustable levels: High/Mid/Low
Thermal Rating	59 °C (138 °F)	Maximum temperature tolerance
Air Velocity	0–4000 fpm	Detection under airflow
Operating Temp.	-10 °C to 50 °C	Environmental range
Humidity	0–95 % RH non-condensing	Tolerance to moisture

Table V: Mechanical Specifications

Parameter	Value
Height	46 mm with base
Diameter	100 mm dia
Weight	150 g with base
IP Rating	IP42

Table VI: Compatible Devices

RE314B	Normal Base
RE314BI	Isolator Base

Wiring Diagram:

Refer to Fig. 10. for the multi-sensor detector connection layout.

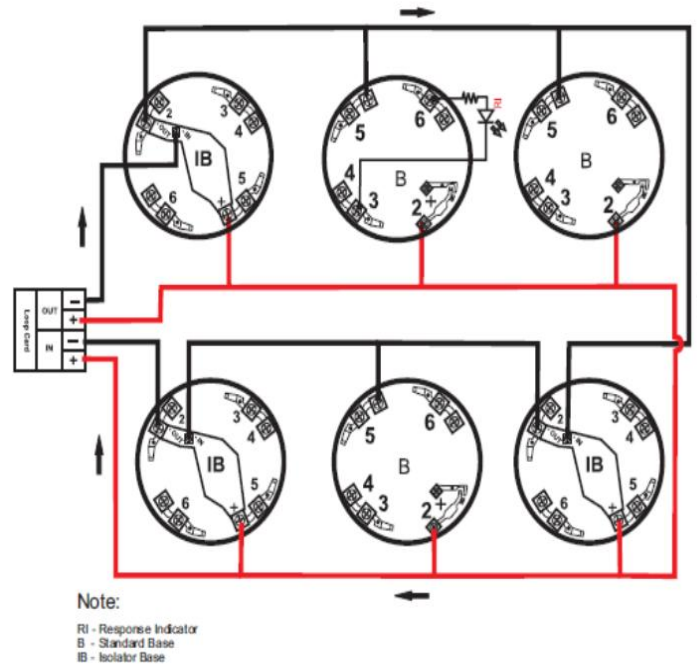


Fig. 10. Wiring Diagram

**D. Proposed Fire Suppression System**

The flammability of carbonaceous dust a foam based sprinkler system of mist is suggested. The system is also applicable with localized incidents using dry-chemical or CO<sub>2</sub> suppression. Key benefits include:

- Quick cooling and fire suppression of storage tanks.
- Reduced fire spread on carbon rich settings.
- Automated response to multi-sensors.

**V. CONCLUSION AND FUTURE WORK**

This study describes a superior fire detection system of carbon storage plants with the help of Fire Dynamics Simulator (FDS). Environment of carbon storage is highly problematic since most of the fires occurring are smoldering fires and are low heat release, low visible smoke, and low stage gas emission (carbon monoxide, carbon dioxide). The traditional type of fire detection systems that are usually based on smoke sensing or even heat sensing do not give time warnings, on time to causes fire spread, loss of material and sometimes people may suffer injuries.

By employing FDS simulations, which involves CFD, this paper investigated fire spreading, smoke development, temperature change and species of the gases in the presence of typical carbon storage conditions. The findings have shown that multi-sensor detection systems, which combine smoke, heat and gas sensors with each other can greatly shorten the time of detectors as opposed to the conventional single parameter detectors. The early fire detection performance can be further improved with optimized location of such sensors with the help of simulation data. Moreover, carbon-rich environments were found to have an additional response to fire control, which is foam-based fog- Sprinkler and suppression systems, which had the capacity to reduce both smoldering and flaming fires.

The suggested solution offers a performance-based model to the design of the dependable and effective system of fire detection and suppression in carbon warehouses. It underscores the imperative of simulation-based analysis to deal with a special difficulty that smoldering fires and combustible dust hazards present. Improving accuracy of early fire detection and reducing the number of false alarms through the introduction of artificial intelligence and real-time data analytics can be the area of future work, along with more experimental validation of the simulation predictions using large-scale tests. Other research may also portray the modeling of dust explosion conditions, optimization of sensor networks to the storage of variables and ventilation conditions, and research on hybrid suppression using foam, gas, and water mist to further enhance the fire safety of multi-material storage facility.

**REFERENCES**

- [1]. X. Yang, Y. Li, and Q. Chen, "Automated image-based fire detection and alarm system using edge computing and cloud-based platform," *Internet of Things*, vol. 28, pp. 1–12, 2024.
- [2]. L. Xu, L. Cheng, J. Ji, Q. Wang, and M. Fang, "A comprehensive CFD combustion model for supercritical CFB boilers," *Particuology*, vol. 43, pp. 29–37, 2019.
- [3]. A. Kashef, N. Benichou, G. Lougheed, and A. Debs, "Computational fluid dynamics simulations of in-situ fire tests in road tunnels," in *Proc. 5th Int. Conf. on Tunnel Fires*, London, U.K., 2004, pp. 185–196.
- [4]. Y. Xin, J. P. Gore, K. B. McGrattan, R. G. Rehm, and H. R. Baum, "Fire dynamics simulation of a turbulent buoyant flame using a mixture-fraction-based combustion model," *Combustion and Flame*, vol. 141, no. 4, pp. 329–335, 2005.
- [5]. W. Jahn, G. Rein, and J. L. Torero, "The effect of model parameters on the simulation of fire dynamics," *Fire Safety Science*, vol. 9, pp. 1341–1352, 2008.
- [6]. C. Zhang and G. Q. Li, "Fire dynamic simulation on thermal actions in localized fires in large enclosures," *Advanced Steel Construction*, vol. 8, no. 2, pp. 124–136, 2012.
- [7]. K. B. McGrattan, H. R. Baum, R. G. Rehm, A. Hamins, G. P. Forney, J. E. Floyd, and K. Prasad, *Fire Dynamics Simulator—Technical Reference Guide*, Gaithersburg, MD, USA: NIST, 2000.
- [8]. E. Ghadirian and H. Arastoopour, "CFD simulation of a fluidized bed using the EMMS approach for the gas–solid drag force," *Powder Technology*, vol. 288, pp. 35–44, 2016.
- [9]. E. Ghadirian and H. Arastoopour, "Numerical analysis of frictional behavior of dense gas–solid systems," *Particuology*, vol. 32, pp. 178–190, 2017.
- [10]. T. G. Fernandes, G. H. Fiorot, and F. M. Pereira, "CFD simulation and validation of a fluidized bed experiment using different drag models," in *Proc. 25th ABCM Int. Congress of Mechanical Engineering*, Brazil, 2019.
- [11]. P. Kusriantoko, P. F. Daun, and K. E. Einarsrud, "A comparative study of different CFD codes for fluidized beds," *Dynamics*, vol. 4, no. 2, pp. 475–498, 2024.
- [12]. W. Węgrzyński and T. Lipecki, "Fire and smoke modelling," in *Handbook of Fire and the Environment: Impacts and Mitigation*, Cham, Switzerland: Springer, 2022, pp. 101–181.
- [13]. Bureau of Indian Standards, IS 15908: Selection, Installation and Maintenance of Control and Indicating Equipment for Fire Detection and Alarm Systems—Code of Practice, New Delhi, India, 2011.
- [14]. F. H. Bastiani, P. B. Neto, L. Buss, U. Fritsching, and D. Noriler, "Modeling the carbon black production in an enclosed FSP reactor," *Chemical Engineering Research and Design*, vol. 92, no. 9, pp. 1744–1756, 2014.
- [15]. P. A. Tesner, T. D. Smegiriova, and V. G. Knorre, "Kinetics of dispersed carbon formation," *Combustion and Flame*, vol. 17, no. 2, pp. 253–260, 1971.
- [16]. I. M. Kennedy, W. Kollmann, and J. Y. Chen, "A model for soot formation in a laminar diffusion flame," *Combustion and Flame*, vol. 81, no. 1, pp. 73–85, 1990.
- [17]. M. Frenklach and H. Wang, "Detailed mechanism and modeling of soot particle formation," in *Soot Formation in Combustion*, Berlin, Germany: Springer, 1994, pp. 165–192.
- [18]. A. Y. Watson and P. A. Valberg, "Carbon black and soot: Two different substances," *American Industrial Hygiene Association Journal*, vol. 62, no. 2, pp. 218–228, 2001.
- [19]. G. Xia, J. Ye, Z. Zheng, X. Li, C. Chen, and C. Hu, "Catalytic FeP-decorated carbon black as a multifunctional conducting additive for high-performance lithium–sulfur batteries," *Carbon*, vol. 172, pp. 96–105, 2021.
- [20]. X. Wu et al., "Boosting the electrochemical performance of lithium–sulfur batteries using a carbon black/LiMn<sub>2</sub>O<sub>4</sub>-modified separator," *Journal of Alloys and Compounds*, vol. 835, p. 155251, 2020.
- [21]. J.-B. Donnet, R. C. Bansal, and M.-J. Wang, *Carbon Black: Science and Technology*, 2nd ed. New York, NY, USA: Marcel Dekker, 1993.
- [22]. C. O. Okoye, I. Jones, M. Zhu, Z. Zhang, and D. Zhang, "Manufacturing of carbon black from spent tyre pyrolysis oil: A review," *Journal of Cleaner Production*, vol. 278, p. 123348, 2021.
- [23]. M. Ciobanu, A.-M. Lepadatu, and S. Asaftei, "Chemical and electrochemical studies of carbon black surface by treatment with ozone and nitrogen oxide," *Materials Today: Proceedings*, vol. 45, pp. 4206–4211, 2021.
- [24]. S. Suard and C. Lapuerta, "Verification and validation of a CFD model for simulations of large-scale compartment fires," *Fire Safety Journal*, vol. 88, pp. 15–27, 2017.
- [25]. T. Beji and H. Prêtre, "Computational fluid dynamics simulations of water spray interaction with smoke in confined and mechanically ventilated enclosure fires," *Fire Safety Journal*, vol. 91, pp. 771–784, 2017.
- [26]. H. Prêtre and J. M. Such, "Effect of ventilation procedures on the behaviour of a fire compartment scenario," *Fire Safety Journal*, vol. 89, pp. 35–49, 2016.
- [27]. NIST, FDS–SMV User and Technical Manuals, National Institute of Standards and Technology. [Online]. Available: <https://pages.nist.gov/fdssmv/manuals.html>