

PAST, PRESENT AND FUTURE FOR ENCLOSURE FIRE FIELD MODEL

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Abstract. *Computational fluid dynamics (CFD) analysis became a popular solution as the complexity grew in applying the laws of physics directly to real fire scenarios in order to make analytical predictions. This fact became especially prevalent for fluid dynamics and heat transfer engineering problems for enclosure fire. The fire field model consists of the CFD code and the fire model. The CFD code is the core and provides the fire model with transport mechanisms for energy, momentum, mass. The fire model is a detailed specification of the fire description. The use of the fire field model in the enclosure strengthened our understanding of the actual fire scene, allowing us to fully characterize the time-dependent changes. The paper delivers a comprehensive review of the history, development, current state of field models and future predictions in enclosure fire field modeling.*

Key words: *computational fluid dynamics, fire dynamics simulator, zone model, enclosure fire, fire field model*

1. INTRODUCTION

Computational fluid dynamics (CFD), can be seen as a group of computational methodologies that encompasses the earlier methodologies and works to decide which set of physical assumptions and related equations need to be used for the particular problem at hand.

On a technical level, there are two dominant approaches to CFD, finite difference and finite volume. In both cases, CFD approximates the spatial domain into a grid or mesh and marches the numerical solution forward in discrete time steps. Depending on the flow conditions, different approaches to discretization and time marching may be favored on an application-specific basis.

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Enclosure fire studies demand multiple modeling techniques to describe the complex behaviors of fire dynamics. The fire models can be: probabilistic or deterministic.

Probabilistic models do not make direct use of the physical and chemical principles involved in fires, they make statistical predictions about the transition from one stage of fire growth to another. Time-dependent probabilities are ascribed to the possibility of the fire changing from one stage to another, and approximations are based on experimental data and fire incident statistics. This approach to the enclosure fire phenomenon is beyond the scope of this work and is not discussed.

Deterministic models in fire safety engineering can be divided into categories, depending on the type of problem to be addressed. Deterministic models include; hand calculation, zone model, and CFD. All those models have some advantages and disadvantages (Figure 1).

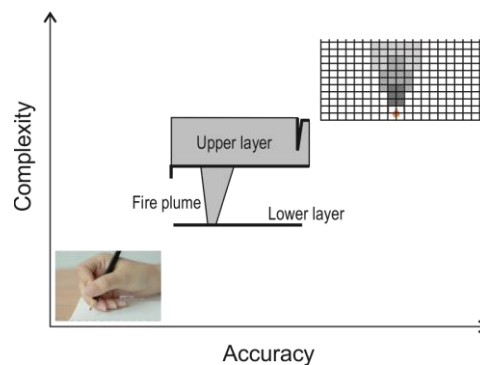


Fig. 1 Deterministic models; Hand calculation, Zone model and CFD model.

Hand calculation can be done by using simplified equations that rely on commonly applied assumptions. Assumptions imply the user must be aware of the limitations of a method.

Hand calculations analytically describe some basic fire processes, and can help to determine if it is necessary to perform more detailed calculations using a zone or CFD models.

Using zone and CFD models in fire safety engineering design is not simple or easy, no matter how “user-friendly” the computer program may be. The user must have an understanding of the physics and chemistry of enclosure fires in order to provide appropriate input values and assess the validity and accuracy of the simulation results.

Several so-called “Round Robin” studies have been conducted where a number of professionals in research or engineering are asked to use a model to simulate a given experimental setup or an enclosure fire scenario, and their simulation results are compared. Such studies have shown that there can be a considerable discrepancy in the results depending on the user and the user’s assumptions made on various input data [1].

Enclosure fires are based on the time-dependent, three-dimensional solutions of the fundamental conservation laws, prevalent for fluid dynamics and heat transfer engineering problems. Therefore, this paper will concentrate on deterministic field models for enclosure fires, zone modeling and CFD modeling.

2. ZONE MODEL

The Consolidated Fire and Smoke Transport (CFAST) computer fire model was first publicly released in June 1990, following a decade of development of what is now referred to as zone models.

The C in CFAST, “Consolidated” implies that this model was intended to bring together into a single package the advancements that had been made at the National Institute of Standards and Technology and elsewhere. In 1992 various zone fire models were developed, up to 31 in all.

A survey conducted in 2003, by the engineering firm Combustion Science and Engineering website, holds a list of 25 various types of models for fire and smoke zone modeling. But of all these, only two are now actively supported: CFAST and ARGOS zone models [2].

The zone model represents the system as two distinct enclosure gas zones: an upper volume and a lower volume resulting from thermal stratification due to buoyancy. Fire is a source of energy and mass and manifests itself as a plume of mass from the lower zone to the upper zone through a process called entrainment. An essential feature of a zone model is the mass rate of entrainment relationship for the fire plume.

This allows the principal mechanism for flow between the lower and upper stratified gas layers (Figure 2).

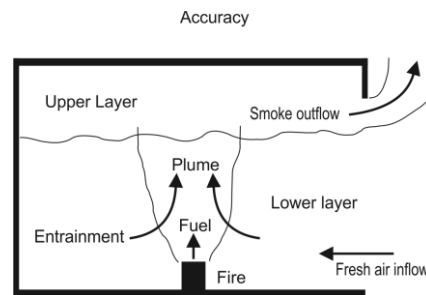


Fig. 2 Zone model stratification

Considerable work has been performed to develop enclosure entrainment relationships for pool fires. Unfortunately, both the ideal theoretical plume models and correlations based on data vary widely and no consensus exists among zone models in practice for the optimum pool fires entrainment model. Even a perfect entrainment relationship for axisymmetric pool fires would not necessarily be perfect in a zone model, because a plume in an enclosure can be subject to nonsymmetric air flows that can bend the plume and thus affect its entrainment rate. Usually, ventilation change will increase the entrainment rate [3].

Some of the enclosure fire effects are absent from the zone modeling approach - good examples are transient flow in corridors and shaft flows. Transient corridor flows are important in the analysis of smoke transport along long corridors [4]. The current zone modeling would yield an instantaneous layer that would descend, but the actual process produces a transient ceiling jet. Flows up vertical shafts involve the interaction of plumes with walls, pressure-driven effects and turbulent mixing (Figure 3) [5].

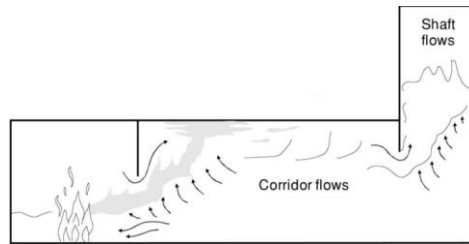


Fig. 3 Transient flow in corridors and shaft flows

The zone models have been constructed with the purpose of treating a fire in a single cubical enclosure or a series of connected enclosures whose sizes are representative of domestic rooms, offices or small industrial units.

The zone models show a good agreement with experiments carried out in such enclosures, with regard to temperature and smoke layer height predictions [6].

The zone modeling may not be suitable for some other geometries, such as smoke spread in enclosures with a large length-to-width ratio or enclosures where the horizontal length-to-vertical length ratio is very large or very small.

As an example, ISO discusses aspect ratios and states that caution is needed for enclosures where length divided by width (L/W), or height divided by width (H/L), is larger than about 5 [7]. Accordingly, zone models may not be appropriate for modeling fires in long hallways or tall shafts. It is a decrease in the use of zone modeling, and as a reason can be stated that it is no longer an area of active research, and reduction of the market is economically viable.

Developing a zone model is the easy part, the hard part is verification and validation, documentation, version control, and software quality assurance, in other words, maintenance. CFAST is now what it was originally intended to be a simple two-zone, multi-enclosure fire model that is relatively easy to set up and run.

Figure 4 shows the graphical user interface: the tabs along the top of the screen lead the user in a logical progression, starting with the enclosure geometry and materials, through doors and vents, mechanical ventilation, the fire and fire protection devices like sprinklers and smoke detectors.

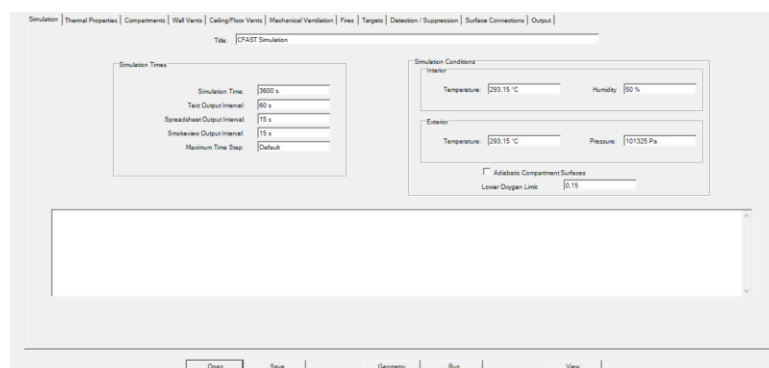


Fig. 4 CFAST Grafical user interface

A question arise by itself, is there anything new in CFAST? Not really.

A useful improvement to CFAST is the use of Smokeview for visualization. Smokeview was originally designed as the graphics component of FDS but it has been extended to include the output of CFAST.

The argument will be that zone models are out of date, but regulatory authorities like the U.S. Nuclear Regulatory Commission and the U.S. Department of Energy, as well as the Society of Fire Protection Engineers, assert that zone models, along with even simpler empirical enclosure fire models, still have their place in performance-based design.

3. MULTI-ZONE MODEL

The new approach to zone modeling is currently under the development and testing phase, named the Multi-Zone model (MZ).

There have been previous efforts to produce a model with multiple zones and improve the abilities of a zone model while still using significantly less computing power than a CFD model. The Multi-Layer zone model (MLZ) was developed to predict vertical variations in temperature and concentrations of chemical species in enclosure fires by dividing an enclosure into many vertical layers instead of just two layers like a conventional zone model. The overall concept of an MLZ is visualized in Figure 5, and a general description has been presented in publications [8].

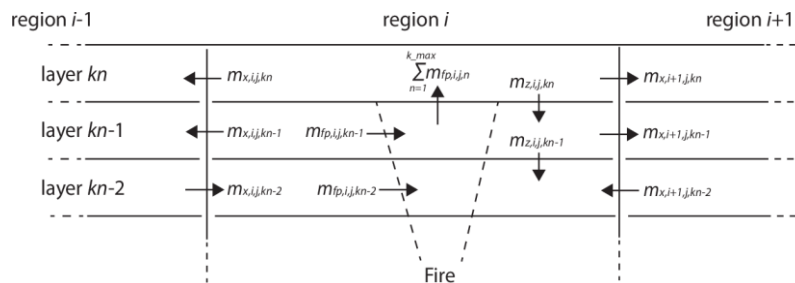


Fig. 5 MLZ model concept, re-drawn from Suzuki et al., 2004.

Like a zone model, the MLZ model uses equations for the conservation of mass and energy but applies this method for the boundaries between each vertical layer while still allowing the plume to rise through the layers until it hits the ceiling. The MLZ model assumes temperature and species concentration to be uniform in each separate layer which effectively means the model produces a two-dimensional model of an enclosure.

The MLZ model was later modified so that the volume could be divided horizontally into several cells to calculate horizontal variations in gas temperatures and species concentration in two directions. Even though the modifications it is still a 2D model and can have applications in long narrow enclosures like tunnels or corridors.

The MZ model is based on the same principles as the MLZ model, but a major difference is that the MZ model divides an enclosure into multiple cells into three dimensions. MATLAB must be used for data visualization, since there is no option to visualize data from the MZ model (Figure 6).

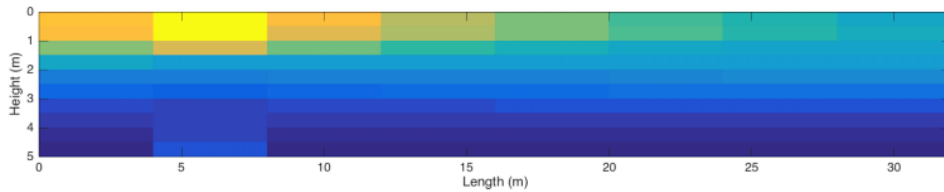


Fig. 6 Illustration of Multi-Zone fire model in an enclosure as tunnel approximation, rendered with MATLAB [9].

Although the two models share the same basic principles, parts of the MZ model are based on publications on the MLZ model. It is unknown if there are more similarities between the two models since the code for the MLZ model has not been published. The MZ model can be seen as an improved version of the MLZ model.

The goal of the MZ model is to combine the ability to split the room into multiple zones in a similar way to a CFD model but still be able to run simulations of large enclosures without needing large amounts of computing power.

The evaluation study of the MZ concept is performed by comparing data from an MZ fire model to previously published experimental data and data from simulations with FDS [10]. The results presented in the evaluation study show that the MZ fire model predicts gas temperatures within 5% of FDS results and within 10% of the experimental data in two well-ventilated large enclosures. In some cases, there is a discrepancy between the modeling and the experimental data. The assumption, of the limited ventilation in the experimental test, is not explained in the description of the experiment.

The main benefit of the MZ model is that simulations of scenarios like the ones used in the evaluation are performed within 1 – 2 minutes. This is in the order of 0.1% of the time to perform a similar FDS simulation.

4. FDS

Increased interest in the use of computational simulations started in the 1960s and 1970s for problems like the design of aircraft and rockets. These simulations involve flow speeds where acoustic waves are important, and were not applicable for a fire scenario.

The more realistic approach to fire simulations is accomplished by Ron Rehm and Howard Baum in 1978, with a simplification of the Navier-Stokes equations for low-speed flows, which is typical for fire scenarios [11].

Cox et al. (1989) utilized one of the first fire field models to investigate the King Cross Fire in the London Underground Station, which was a tragic fire disaster that caused 31 deaths on 18 November 1987. [12].

In the early 1990s, there was an interest in examining problems such as the effectiveness of vents and draft curtains in warehouses, geometric obstructions to represent rack-stored commodities, turbulence models, terrain, features of sprinklers and heat conductions.

The numerical study reported by Yeoh et al. (2003) showed that the incorporation of combustion, soot and radiation models improved the temperature field prediction in enclosure fires [13].

A significant change was made with the development of tools called A Large Outdoor Fire Plume Trajectory (ALOFT) and Computational Fluid Dynamics (CFD) referred to as the industrial fire simulator [14].

Since fire field models were proven useful for fire engineering solutions in many studies, it has become one of the major research interests in fire dynamics.

4.1. FDS version 1

Development continued on the industrial fire simulator, and Dynamics Simulator Version 1 (FDS 1) was publicly released in February 2000.

There is a capability to run both direct numerical simulation (DNS), as well as large eddy simulation (LES) calculations, intended for length scales of practical engineering problems.

A review of FDS techniques applied in fire research pointed out that the sub-grid features offered by the LES model would be an appropriate tool to account for the randomness of fire behavior. Inputs were developed to easily specify boundary conditions such as open boundaries or inlets, exit flows, the size, location and thermal inertia of obstructions. The basics of what is recognized as FDS existed in a simple grid with obstructions defined as if they were made from bricks.

Fires were represented as particles that emit heat (yellow) and then become inert (black), as shown in Figure 7a. The LES approach in fire simulations significantly improved the modeling of the flame structure (Figure 7b).

"Smokeview" is a phenomenon that was created to aid in the visualization of fire for better comprehension [15].

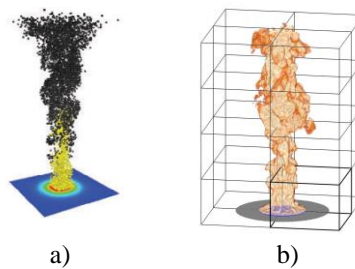


Fig. 7 a) FDS 1: Pool fire model; b) FDS 6: Pool fire model

4.2. FDS version 2

FDS 1 worked well in cases where well-ventilated fires were small in comparison to the volume of the space. Applying FDS to enclosure fires required an "in-the-box" approach. For modeling combustion in an enclosure, a mixture fraction combustion model was developed.

The mixture fraction was a major step forward for FDS. There was a combustion model that depended on available oxygen, a flame volume for radiation, and product gases for a radiating hot layer or evaluating tenability. For modeling radiation, a discrete-ordinates (DO) model was formulated and solved numerically by a finite-volume method (FVM).

Any gas cell or wall cell can radiate heat over either a full sphere (emission from a gas cell) or a half sphere (emission from a wall cell). This model was simple and robust. It could predict radiation from hot layers and resolve the shadowing that occurs when an

obstruction is between the fire and a target. FDS 2 was released in December 2001 with updates through 2002.

4.3. FDS versions 3 and 4

Following the attacks on September 11, 2001, the Building and Fire Research Laboratory at NIST was tasked with investigating the collapse of the World Trade Center buildings. The need for these investigations drove much of FDS development during the 2001 to 2005 period.

The need for the large domain to model multiple floors of the World Trade Center towers spurred the development of multiple mesh capabilities and the use of Message Passing Interface (MPI) to perform a simulation over multiple computers. FDS had to model multiple floors of a large building, including the effects of fire spread, window breakage and ventilation-limited combustion.

To improve FDS results for ventilation-limited combustion, a simple extinction model based on cell temperature and oxygen mass fraction were added. FDS 4 was released in March 2006.

4.4. FDS version 5

The U.S. Nuclear Regulatory Commission had begun a Verification and Validation (V&V) effort of a number of fire models, including FDS. It was recognized that FDS had become much more than a research tool and that simply providing download links for an executable and a zip file of the source was not the best way to manage FDS development.

This realization sparked a lengthy effort to impose some modern software development practices on the FDS project. During this period the entire FDS project was hosted online briefly at SourceForge, followed by a lengthy period on GoogleCode.

The online presence for FDS also included a discussion forum where users could assist each other with FDS as well as an issue tracker where users could report problems with FDS. The increased use of FDS had also exposed limitations of the mixture fraction combustion model, the available FDS boundary conditions when modeling fires in buildings, and the droplet evaporation model. The mixture fraction model was replaced with an eddy dissipation model where three “lumped” species (fuel, air and products) were tracked. This allowed unburned fuel to coexist with air following extinction, which was not possible with the mixture fraction approach.

Twenty-seven versions of FDS 5 were released between 2007 and 2010. Those versions allowed different background pressures in different rooms and control functions for opening and closing vents or removing obstructions, and expanded the ability of FDS to model fires in enclosures.

4.5. FDS version 6

Several studies have been conducted regarding the connection between cell size and characteristic fire diameter to save computational time.

FDS uses second-order accurate approximations of both the temporal and spatial derivatives of the Navier-Stokes equations, meaning that the discretization error is proportional to the square of the time step or cell size [16]. Reducing the cell size by a factor of 2 will theoretically increase the computing time by 16 times while the discretizational error

is decreased by 4 times. A measure of how well the fire is resolved is given by the non-dimensional expression, $D^*/\delta x$, the so-called “resolution index” (Eq. 1).¹

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_\infty T_\infty \sqrt{g}} \right)^{2/5} \quad (1)$$

where:

δx – nominal size of a grid cell

D^* – characteristic fire diameter

ρ – density

T – temperature

c – constant pressure specific heat

\dot{Q} – total heat release rate

g – acceleration of gravity

What is the “right” value of the resolution index? There is none, but for purpose of grid resolution studies, the FDS validation suite contains examples where the resolution index chosen is 5, 10, and 20.

In support of software development and software quality assurance, a series of tools called Smokebot, Firebot and Validationbot are developed. These tools form a suite that performs continuous integration testing.

Smokebot is a tool that tests every change to the source code to ensure that it compiles successfully and can successfully run a small set of test cases. Firebot is a tool that runs daily basis; it clones a new copy of the FDS repository, compiles FDS, runs all of the verification cases, compiles all of the FDS documentation and checks everything for errors.

During the development of FDS 6, GoogleCode shut down its hosting of non-Google projects. This forced migration of the project to Github. With Github, anyone can clone the FDS repository, make a change to the source, add a new verification case, add a new experimental dataset and validation cases, or any other change and then share that change with developers who can then discuss whether to accept the change into the official source code. FDS 6 have been released on January 2017 and the current version is in September 2022, FDS 6.7.9.

5. FUTURE FOR ENCLOSURE FIRE FIELD MODEL

FDS represents the most sophisticated deterministic field model for enclosure fires. The FDS modeling technique is used in a wide range of engineering disciplines and is based on a complete, time-dependent, three-dimensional solution of the fundamental conservation laws.

In recent years we have seen large wildland fires impacting cities and large areas. Modeling these fires requires capturing large-scale atmospheric conditions and flows over large regions as well as the small-scale details of flame fronts. This is driving the development of a number of items: better support for massively parallel computations,

¹ The characteristic fire diameter is related to the characteristic fire size via the relation $\dot{Q}=(D^*/D)$, where D is the physical diameter of the fire.

new methods for modeling atmospheric flows and embedded meshes for allowing local refinement as needed.

Currently, one of the biggest limitations of the FDS approach to parallel computing is that the current pressure solver can only operate on one mesh at a time. Thus, each mesh does its own solution, all of which must then be stitched together before updating the flow field. This is still a major source of numerical issues. Work is underway to develop a global pressure solution that would solve overall meshes simultaneously, while still maintaining fast execution speed.

The most promising alternative to the problem is cloud computing. The simplest defining cloud computing is the usage of online computing resources or services, with reduced or nonexistent effort to configure, maintain and scale them to user needs. Software as a service (SaaS) is a software licensing and delivery model in which software is licensed on a subscription basis and is centrally hosted. SimScale is the world's first production-ready SaaS application for engineering simulation. SimScale's cloud-based fluid dynamics software enables users to test, validate and optimize designs through online CFD.

The increased interest in predicting the fire structure interactions also spurs interest in accurately representing steel structures in the model. Unstructured geometry is being developed so that a user could specify a curved surface as a curved surface without having to manually divide it into blocks.

Better capabilities for under-ventilated fires (CO predictions), the ability to accurately capture the effects of gaseous and water mist suppression systems and to make predictions of flame spread over 3D items are also needed. Work is underway to develop improved extinction and re-ignition models, 3D heat transfer models and improved pyrolysis capabilities as well as support for cloud computing to address these needs.

Cloud-based computer-aided engineering (CAE) and CFD software have pushed the boundaries for more complex or faster simulations, as well as collaboration and efficiency in the design workflow.

6. CONCLUSIONS

Having benefited from technological advancement in computing speed, simulation techniques and software algorithms in terms of parallelization techniques, fire field models have been extended to a broader range of practical fire engineering studies.

The use of field models in enclosure fires strengthened our understanding of the actual fire scene, allowing us to fully characterize the time-dependent changes in temperature, velocity, chemical gas species and soot particles.

With the development of cloud-based CAE, it can be said with some degree of certainty that resource-draining hardware applications will become less and less relevant, nonenvironmentally friendly and uneconomical processes of the past. Future perspectives in fire protection engineering will strongly rely on the use of fire field models.

Field models are still used as an additional analysis tool and not a replacement for practical experiments, but it certainly helps decrease costs and verify predictions.

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PROŠLOST, SADAŠNJOST I BUDUĆNOST REALNOG MODELA RAZVOJA POŽARA U POLUZATVORENOM PROSTORU

Metode analize požara zasnovane na proračunima dinamike fluida (CFD) su sve popularniji alat koji omogućava praćenje kompleksnih uzajamno promjenjivih parametara požara, sa ciljem određivanja analitičkih pretpostavki toka razvoja požara. Poseban doprinos imaju u rješavanju problema prijenosa toplote i dinamike fluida u požarima unutar poluzatvorenog prostora. Realni model požara se formira na osnovu CFD proračuna i parametara požara. Pri tome, CFD predstavlja osnovu proračuna prijenosa energije, momenta i mase dok se detaljna specifikacija požara definiše modelom požara. Upotreba realnog modela požara u poluzatvorenom prostoru značajno doprinosi razumijevanju stvarne požarne situacije, omogućava opis i vizualni prikaz promjena u realnom vremenu tokom razvoja požara. Cilj rada je dati detaljan uvid u istoriju, razvoj, kao i trenutna ograničenja realnog modela požara te ukazati na budućnost u primjeni realnog modela u analizi razvoja požara.

Ključne riječi: proračun dinamike fluida, simulator dinamike požara, model zone požara, požar u poluzatvorenom prostoru, realni model razvoja požara