ABSTRACT

The idea of predicting fire growth, fire heat release rates, and smoke conditions in tunnels and metros has lived for a long time in the minds of researchers and tunnel fire life safety practitioners. As technology evolves, many seek to develop and use new tools. This has been the motivation behind many experiments, both scaled, and full-size. But, to date, many have not solved the problem because they do not understand it, or they do not want to do what it takes to solve for it. Many claim that the problem is too complex and seek to over simplify the problem to the point that calculations have a large error margin.

This paper presents what the author considers to be the most advanced and only fire model available in the industry capable of predicting fire growth, fire spread, flashover (if attainable), peak heat release rate, steady-state fire heat release rate, and eventually fire decay, and its corresponding smoke products. This is achieved using Computational Fluid Dynamics performing close to reality geometry, full combustion, with radiation, thermo-physical properties, and fire performance data. The result is very robust and provides a visualization of how a fire generates smoke, and heat, and how the spread of them is through a three dimensional space.

Keywords: fire heat release rate, fire modelling, tunnel ventilation, fire life safety in tunnels

1. INTRODUCTION

In recent years, 2004 to be exact, Ingason and Lönnermark (2004) published a paper presenting an overview of the latest information available about Fire Heat Release Rate (FHRR) in tunnels, ranging from 6 to 300 MW. What the data shows is that the predicted FHRR varies all over the place. The paper does not identify uncertainty, nor how reliable the numbers are. Chiam (2005) provided a review of various methods used in the past to estimate FHRR not in a critical manner, but rather in a list manner. This review lists experiments made and FHRR adopted by some systems around the world, which vary very much. No insight as to why such variation on the estimate.

Sanchez (2008) discussed that in order to improve the accuracy of the predictions, numerically or experimentally, the physical models must be improved accounting for key physics in the fire phenomenon. In addition, the thermal physical properties, and fire characteristics of the materials that will potentially get involved in a fire must be known. Sanchez identified weaknesses in using the oxygen consumption method, which is considered the most accurate method to evaluate FHRR from experiments. Sanchez identified a miss conceptions made by many in the interpretation of \( \dot{m}_{\text{fuel}} \) (kg/s), which many interpret as mass flow rate in stead of mass burning (reacting) rate (see Equation 1). After all, a fire is a chemical reaction; not a convective heat transfer problem alone. A proper way to model a fire is by accounting for air depletion (Equation 2).
Some approximate smoke from a fire assuming one gas phase (air), and smoke as a scalar. The assumption is that the presence of the smoke is in such a small concentration, and does not affect the thermo-fluid physical properties of the flow field. Such is the case of a smoke gas tracer. However, smoke from a fire is not negligible (large concentrations), and has a tremendous impact on the thermo-fluid physical properties of the flow field. In this case, smoke cannot be modelled as a scalar, but must be modelled as a multi-component fluid solving species transport equations.

\[
\dot{Q}_{fire} = \dot{m}_{fuel} \cdot burning \Delta H_c \neq \dot{m}_{fuel} \cdot flow \ c_p \Delta T = \rho_{fuel} \cdot v \cdot A \ c_p \Delta T = \dot{Q}_{convective} \tag{1}
\]

\[
1 \ kg_{fuel} + (AFR)kg_{air} \rightarrow (1+AFR) \ kg_{products} + heat \tag{2}
\]

Another misconception made by engineers is that the fire is an stoichiometric reaction, with constant heat of combustion, \(\Delta H_c\). Sanchez illustrated that \(\Delta H_c\) varies as a function of the equivalence ratio, \(\phi\), and temperature. The richer the combustion, and the higher the temperature of the reacting gases, the lower \(\Delta H_c\). Figure 1 illustrates such relation for gasoline at various \(\phi\) and temperatures. The products of combustion also vary as a function of the equivalence ratio, \(\phi\), and temperature, as illustrated in Figures 2 and 3. The fact remains that we all know that incomplete combustion is present in all the uncontrolled fires we use as design fire scenarios. Therefore, it is quite possible that the experimental data reported may be exaggerated because the oxygen consumption method is based on stoichiometric conditions (complete combustion) and \(\Delta H_c=13.1\) MJ/kg of oxygen consumed, which is valid only at a temperature of 298 K. (Janssens, M., (2002), Drysdale (1998))

![Heat of Combustion for Gasoline-C\textsubscript{8}H\textsubscript{18}](image)

**Figure 1:** Heat of combustion for gasoline as a function of \(\phi\) and temperature.
2. FHRR MODEL

It needs to be understood that engineers rely on the models they create. Everything engineers do is an approximation to reality. These models depend not only on the mathematics used, but on the assumptions made. Sanchez (2006) provided an introduction of this advanced model using CFD.

In mathematics, we learn that as we decrease the size of the domain, our differential equations improve in accuracy. So is the case with time, as we decrease the time step, our accuracy also increases. But, let us not forget the properties required to solve the problem. From a fluid dynamics point of view, we need to know density, viscosity, thermal conductivity, and specific heat of the fluid. These properties are required to predict the mass and heat transfer.
in the fluid phase. From a fire point of view, we need to know density, thermal conductivity, specific heat, ignition temperature, and burning mass loss rate of the combustibles. It is interesting to note the dependence these properties have with temperature.

To date, many have studied fires and developed models that focus mainly on the gas phase after the reaction. They assume the FHRR in a form of a heat source which does not take into account the reacting mixture of fuel and air. Many postulate that with a heat release rate from a gas burner, the fire models predict well. However, I argue that this is not a fire model; it is merely a heat transfer model.

The chemical reaction, flame, products of combustion, $\Delta H_c$ (as a function of $\phi$ and temperature), radiation, pyrolysis, mass loss, and flammability limits are not modelled. Some claim that the objective of fire modelling is to simplify the problem. The question that comes to the attention is how much simplification this implies.

In order to develop a fire model, we must understand the physics we are trying to represent. Figure 4 depicts a general model for the process. The steps are as follows:

- Allocate combustible mass on the surfaces in a space representing very closely where fire is expected.
- Combustible surfaces are heated by some form of heat source.
- Account for incubation period, a function of thermal thickness of the materials, after which ignition takes place.
- Fuel is converted from solid to vapour through pyrolysis (Equation 3).
- Fuel and air mix (in all our fires, oxygen is provided by air).
- If fuel mixture is within flammability limits, and the gas temperature is above auto-ignition temperature (see Figure 5), a chemical reaction following Equations 4 takes place.
- Depending on the mixture $\phi$, and temperature, $\Delta H_c$ (Figure 1), and products of combustion are predicted (Figures 2, and 3).
- Depending on the localized $m_{\text{fuel-burning}}$, $\Delta H_c$, the FHRR is predicted (Equation 5).
- Radiation from the localized flame will radiate heat to the surfaces passing through the gas, or is absorbed by the soot and remain in the products of combustion. This will contribute to the fire spread and ignition of other surfaces away from the flame.

$$m_{\text{fuel-loss}} \propto Ae^{-E/RT}$$

$$\text{Fuel} + a(O_2+3.79N_2) \rightarrow b\text{CO}_2 + c\text{CO}+d\text{H}_2\text{O}+e\text{O}_2+f\text{H}_2+gN_2+\text{heat}$$

$$\dot{Q} = m_{\text{fuel-burning}} \Delta H_c$$

where:

- $\dot{Q}$ = fire heat release rate (W)
- $m_{\text{fuel-loss}}$ = fuel mass loss rate (kg/s)
- $m_{\text{fuel-burning}}$ = fuel mass burning rate (kg/s)
- $\Delta H_c$ = fuel heat of combustion (J/kg)
- $A$ = pre-exponential coefficient
- $-E$ = activation energy
- $R$ = universal gas constant
- $T$ = temperature (K)
Figure 4: Physical process of a fire

Figure 5: Generic vapor phase flammability diagram
3. FHRR PREDICTIONS

The predictions are achieved using a CFD computer software that allows for the detailed 3D geometry, and the modelling of the transport equations, among them:

- Conservation of mass (fuel burning rate as mass source)
- Conservation of momentum
- Conservation of energy with radiation (FHRR as heat source in flame zone)
- Turbulence
- Conservation of species (air and hot products)

To avoid repetition of these well-known conservation equations, the reader is encouraged to review the user’s manual of the software used (FLUENT 2006).

The turbulence model used in this paper is based on the standard $\kappa$-$\epsilon$, accounting for buoyancy effects, although other models are available, such as RNG $\kappa$-$\epsilon$, Reynolds Stress Model, etc. The Discrete Ordinate radiation model was used.

Figure 6 illustrates a set of predictions made using this advanced fire model for a train in a tunnel, under natural ventilation, and on a 3% slope. The particular thermal and fire properties used are not important at this time. Let us focus on the information provided by this advanced fire model. The setup assuming a constant igniter in the form of a gas burner.

- The first thing to note is that there is a growth period, a flashover reaching a peak FHRR of 2.5 MW, a steady-state, then sharply decaying to the almost constant 700 kW heat release rate provided by the igniter. Let us not forget that $\Delta H_c$, and products of combustion are calculated to follow the calculations illustrated in Figures 1, 2, and 3,

- The average cabin gas (air and hot products) temperature peaks at about 900 °C, and then drops to about 250°C.

- The fuel from the combustible surface burns through pyrolysis, burning near 1000 kg of mass. The model follows the flammability diagram (Figure 5), such that the fuel only burns if the concentrations of fuel and oxidizer are within the flammability limits, and the temperature is above auto-ignition temperature.

- The mass of air is shown to start at about 84 kg, and then drops as the temperature increases to 900°C, but as the temperature drops, the mass of air available inside the cabin increases to almost its original state. This is in agreement with the equation of state for gases.

- Figure 7 illustrates the surfaces that have ignited, as calculated by the CFD model. The ignition temperature was set to be 300°C (used for demonstration purposes in the sample model presented). Radiation, convection on the fluid side, and conduction in the solid side are modelled on the surfaces where there is combustible that has the potential to ignite and convert solid fuel into fuel vapour.

- Figure 8 illustrates how quickly the smoke generated from the fire spreads inside and outside the train.
4. **MODEL VALIDATION**

This model has been validated following ASTM E1355 from a physical-science (thermo-dynamics, heat transfer), and from a system setup point of view. The thermo-dynamics for the chemical reaction, species generation, and $\Delta H_c$, were validated for gasoline, methane, and propane. There are extensive experimental and thermo-physical data for these three combustibles.

The system setup was validated monitoring temperature predictions made in room fire for a sofa burning and trash can fires. The heat release rate was not considered critical because the experiments are based on the oxygen consumption method, while the method presented in this paper accounts for variable $\Delta H_c$.

5. **CONCLUSIONS**

The model presented in this paper represents the state-of-the-art, and the most advanced fire modeling approach in the industry today. There is no doubt that there is an art involved because the engineer has to compose a picture of the key physics in order to predict more realistically a fire and its effects.

The model accounts for fire physics not accounted in other models. This is achieved through the use of CFD, physical geometry, and reaction processes accounted for. It still relies on knowing thermo-physical, and fire performance data for the combustibles.

This advanced model can predict FHRR, smoke, and flame inside and outside a fire compartment – train car to station, vehicle car to road tunnel, etc. These effects have not been studied that extensively, although some claim so.

6. **REFERENCES**


Figure 6: FHRR predictions in a train car in a tunnel

Figure 7: Inside train wall temperature above ignition temperature (set to be 300°C)
Figure 8: Smoke generated from train fire