Lecture fire simulation

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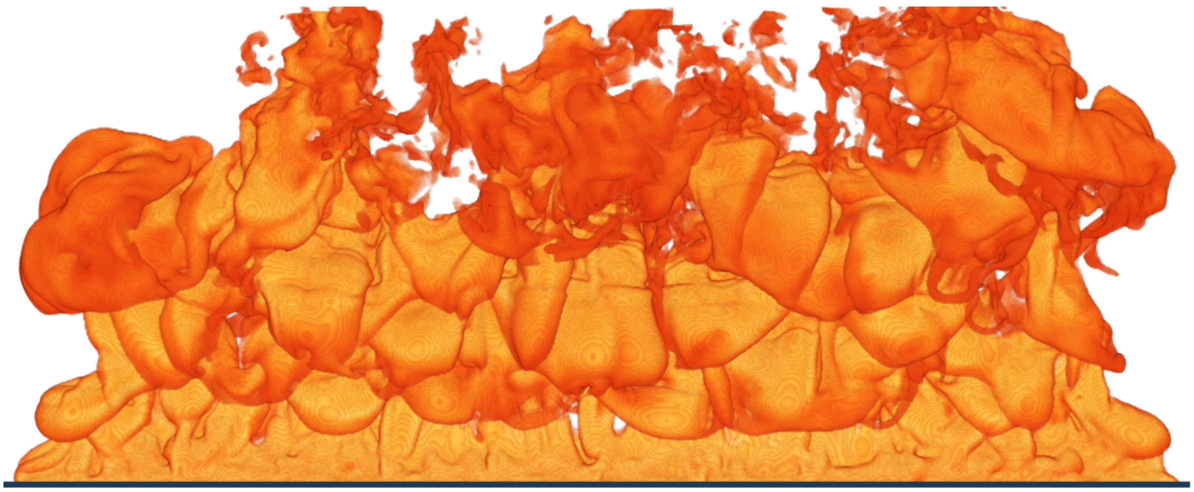
Overview

General Information

The lecture *Fire Simulations* at the University of Wuppertal is organised by the chair of Computational Civil Engineering (CCE). The 2019 founded chair is mainly concerned with the research and development of new computer-based models. The focus of the application is the numerical simulation of fire and smoke propagation in buildings.



This is the first year that we offer this script. The motivation to create this script is on the one hand to give the participants of the lecture a possibility to read the contents. And on the other hand, to make this content freely available to external or former participants.

However, this script is very short and will remain so. Much of the content is already available in greater depth, so that reference is made to the relevant passages - instead of simply copying them.

As the script is under development, we welcome constructive suggestions and your feedback. This way you can support our whole fire science community.

For the University of Wuppertal students: All organisational information on the procedure can be found on the CCE website on the fire simulations lecture.

Contents of the Lecture Notes

- It is planned, that this script will not only contain the contents of the lecture *Fire Simulations* but also other contents linked to this lecture, such as *FDS Data Analysis* and *Using High Performance Computers for Fire Simulations*. In the course of the lecture, we will announce the contents relevant for you accordingly.
- The script also contains exercises for all topics, with and without solution paths, but always with a result or the possibility of validating your solution.
- Do not print out the script or save it elsewhere. This way you have the latest version, which is continuously improved and supplemented with content.
- The script will always remain freely accessible.
- The lecture notes and exercises are designed for **FDS version 6.7.5**, and thus may not be valid / reproducible for other versions.

Contributors

Contributors to the development of the script and the exercises are (in alphabetical order):

- Lukas Arnold
- Kristian Börger
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- Tássia Quaresma
- Jan Vogelsang
- My Linh Würzburger

Theses

We offer theses (BA, MA, PhD) on many different topics.

- an overview of topics and previously supervised theses can be found on the thesis website
- The overview of our publications can also help you find
- If you are interested, please contact Lukas Arnold @ University of Wuppertal or @ Forschungszentrum Jülich

Acknowledgements

The software tools used in the lecture and the creation of the materials are mostly freely available, open source and developed by volunteers. In particular, we would like to thank the following teams for their work

- Team of FDS
- Team of Jupyter
- Team of JupyterLab
- Team of Jupter Book

Contact

How to reach us:

- As a participant of the lecture: best via the associated moodle course
- External interested parties best used our email list.
- Contact details for individuals can be found on the staff website

Part I

Introduction

Team Fire Dynamics

The *Team Fire Dynamics* is a joint team of members of the chair of Computational Civil Engineering (CCE) at the University of Wuppertal (BUW) and the Fire Dynamics division, which is part of the Institute for Advanced Simulation (IAS-7) at the Forschungszentrum Jülich (FZJ).

The CCE chair is mainly concerned with the research and development of new computer-based models. The focus of the application here is fire and smoke propagation in buildings.

In teaching, we focus on computer science and numerics. The main lectures we offer are Computer Science and Fire Simulations. In addition to this, we regularly offer workshops on *data analysis* and *Raspberry Pi*.

The simulation models we develop and use are mostly based on computational fluid dynamics (CFD). In addition, we use genetic optimisation algorithms and image processing methods. What they all have in common is the use of parallel computers, such as the supercomputer JURECA at the Forschungszentrum Jülich.

Figure 1: JURECA supercomputer. Source: Forschungszentrum Jülich

Our research activities include the use and further development of FDS (Fire Dynamics Simulator), which can be used to calculate the spread of smoke and fire in buildings. On the other hand, the development of new simulation tools. These include, for example, the simulation software ARTSS (Accelerator-based Real-Time Smoke Simulator) or PROPTI. The research is carried out in close cooperation with the Fire Dynamics department at the Jülich Research Centre.

Simulation of fires in an underground station, part of the ORPHEUS project, using the software FDS.

Simulation of a liquid fire with the software OpenFoam

Self-consistent simulation of fire spread along a cable route, part of Hehnen, Arnold, and Mendola (2020). Calculated with FDS.

References

Hehnen, Tristan, Lukas Arnold, and Saverio La Mendola. 2020. "Numerical Fire Spread Simulation Based on Material Pyrolysis—An Application to the CHRISTIFIRE Phase 1 Horizontal Cable Tray Tests." *Fire* 3 (3): 33. https://doi.org/10.3390/fire3030033.

Part II

Modeling

1 Modelling Fires

The motivation for this chapter is to provide an overview of the involved phenomena and methods in the modelling of fires. In the first section a brief summary of the physical and chemical processes is given. As one of the application scenarios for fire simulations is fire safety engineering (FSE), the second section outlines some selected aspects of this field of engineering – especially for those who are not familiar with it.

There exist multiple ways to model fires, although this lecutre focuses on field models, i.e. computational fluid dynamics models. In the third section an overview of existing modelling approaches is briefly outlined.

1.1 Physical and Chemical Processes

1.1.1 What is a Fire?

In general: A fire is an exothermic chemical reaction.

Technical Combustion – Wanted Fires

Wanted fires, i.e. technical combustion processes, are **controlled** processes used for e.g. heating or propulsion. Although the term *wanted fire* is somehow misleading, as the fires are typically not wanted and associated with accidents, a bonfire is one of the fundamental wanted applications of fires.

Unwanted Fires

Unwanted fires, are **not controlled and not wanted** processes. These are mostly incidents inside of enclosures and pose danger to wildlife, humans, and property.

Fire Examples

- Bonfire
  - Lakeside Bonfire
  - Slowmotion Bonfire
- Wildland fires
  - Walking With Fire: A Wildfire Documentary

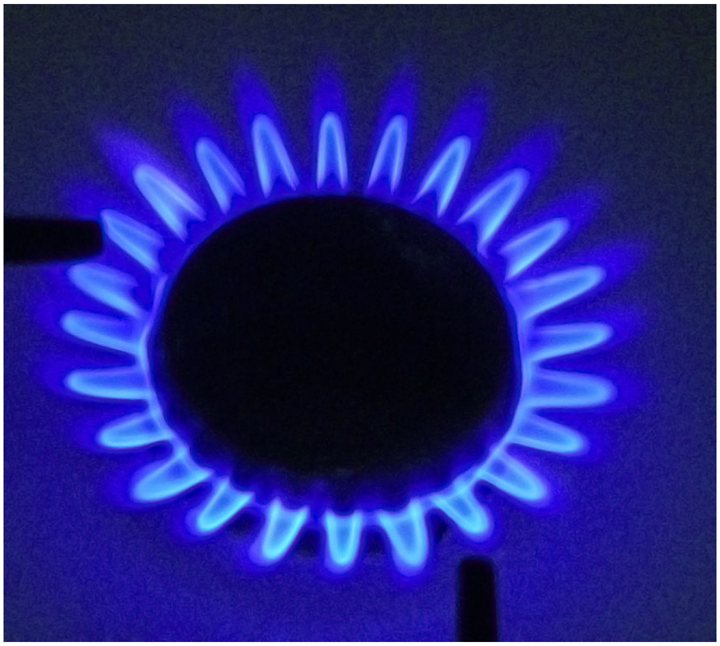

Figure 1.1: In a gas stove, a combustible gas is used to generate heat. The geometry and flow properties of the stove allow a controllable flame. Source: Wikimedia Commons.

Figure 1.2: Bonfires are wanted fires, e.g. for preparing a meal.

Figure 1.3: Building fire. Source: Wikimedia Commons.

  - Indonesia Peat Fires

- Compartment fires
  - Compartment Fire Flashover
  - Storage Fire

1.1.2 Processes Overview

Fires involve a complex interaction of a multitude of physical and chemical processes. While most of them take place in the gas phase, e.g. combustion, fires commonly include also processes in the solid or liquid phase, e.g. pyrolysis which generates the fuel for the combustion. The following processes cover the main phenomena.

1. **Fluid dynamics**
   - fundamental mass and momentum transport process in the gas phase
   - fire related flows are mostly turbulent
2. **Heat transfer**
   - warm gas, e.g. combustion products, are transported upwards by heat convection
   - hot matter emits net thermal radiation
   - heat conduction inside the solid
3. **Combustion**
   - fast oxidation of fuel in the flame
   - release of chemical energy, e.g. locally heating gas or thermal radiation
4. **Pyrolysis**
   - degradation of the solid structure
   - emission of volatile gases, e.g. fuel for the combustion

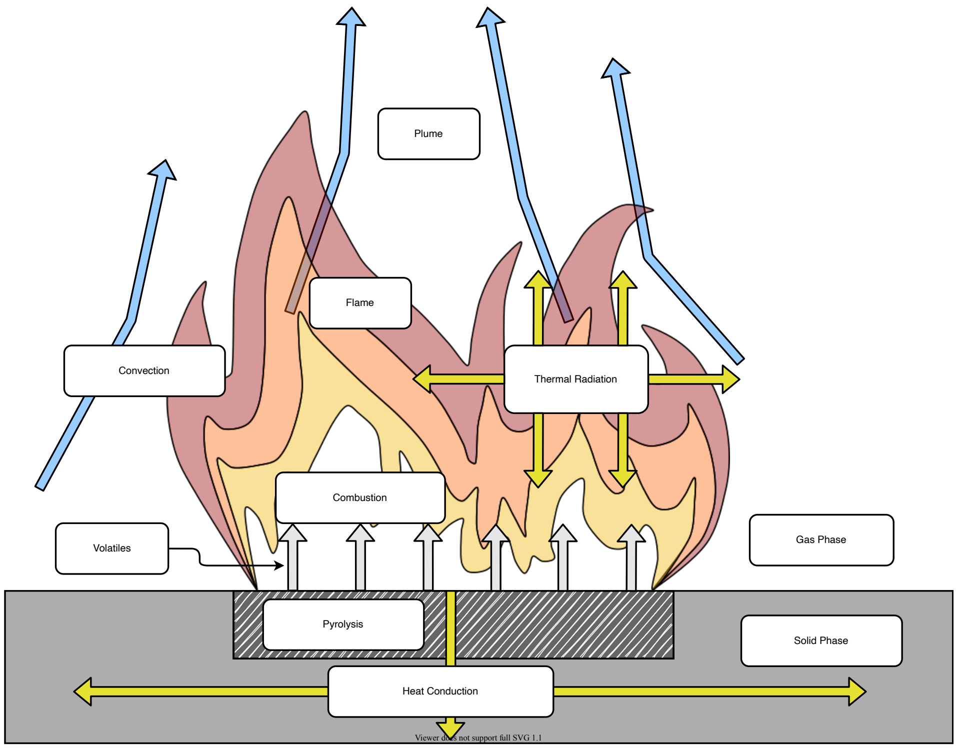

Figure 1.4: Visualisation of the main processes involved in fires.

1.1.3 Fluid Dynamics

Fires induce heat in the gas phase and buoyancy of the heated gas drives a plume. Compartment flows are complex and involve many openings to ambient regions as well as obstructions, see Figure 1.5. Mechanical ventilation, systems for heating, ventilation and air conditioning (HVAC) as well as wind might be included into the evaluation of the dynamics.

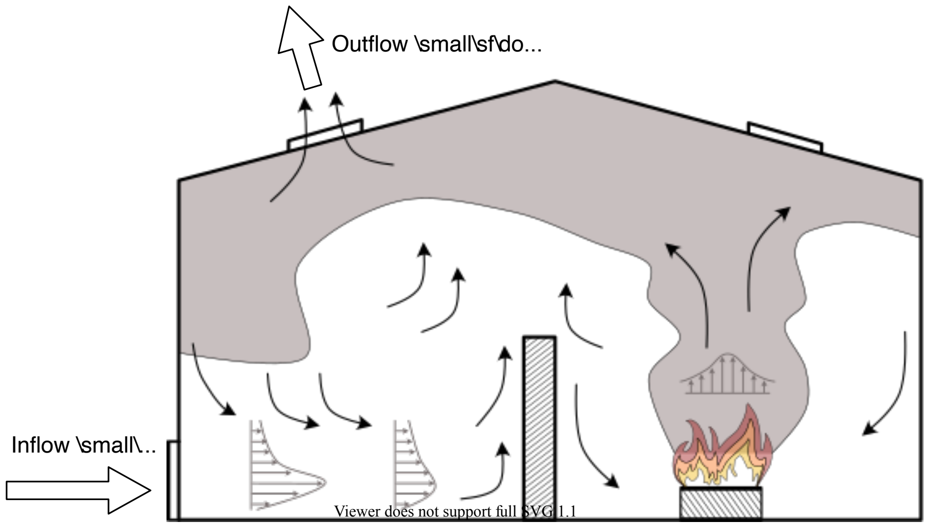

Figure 1.5: Illustration of a potential flow inside a building, driven by the heat released by the fire. There is an inflow and an outflow, which connect the confined flow to the ambient domain.

Most fire flows, especially in the flame and plume region, are turbulent. The turbulent mixture process during combustion is crucial and the entrainment of fresh cold air into a plume significantly determines its dynamics. Experimental analysis as well as numerical models must consider the macroscopic effects of turbulence.

1.1.4 Reactive Flows

Fires are driven by the energy released by combustion, which is an exothermal chemical process. In the simplest case, two gas species, here oxygen and fuel, react and release energy. In real fires, there is a zoo of species and reactions involved. Depending on the concentrations of individual species and their local temperatures, new chemical species can be formed. Thus, the overall spectrum of products, due to the chemical processes during a fire, is rarely simple.

In contrast to technical combustion, in fires the oxygen and the fuel are typically not mixed. The transition from a non-premixed to a premixed combustion can be well observed with a Bunsen burner, see Figure 1.7.

Figure 1.6: Transition from a laminar to a turbulent flow in the plume of a burning candle. The image is captured using schlieren photography, which visualises differences in the refraction index. Source: Wikimedia Commons.

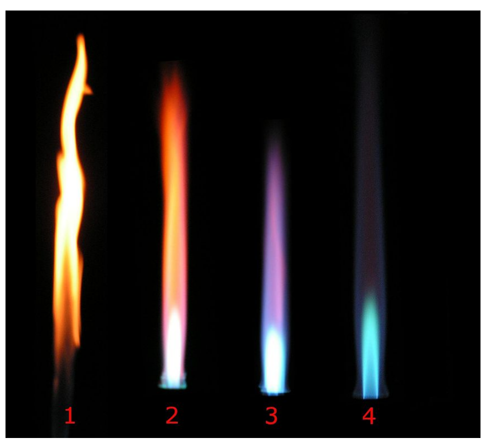

Figure 1.7: Variable oxygen concentrations in the outflow stream of a Bunsen burner. From left to right: air valve closed, nearly fully closed, valve semi-opened and maximally opened. Source: Wikimedia Commons.

The time scales at which the chemical reactions take place span multiple orders of magnitude, see Figure 1.8. Typical combustion processes are much faster than common mass transport processes in fires.

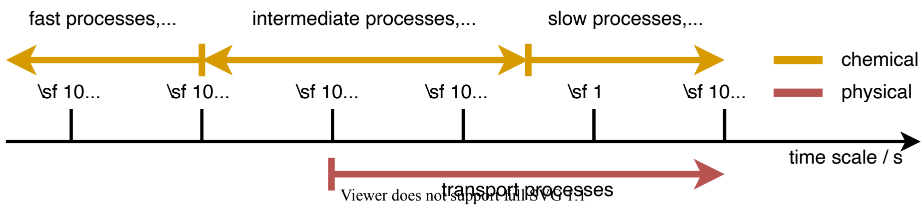

Figure 1.8: (Very) Approximate time scales of chemical and physical processes in reactive flows.

1.2 Heat Transfer

Heat can be transferred between locations and materials in different ways. The flow of heat is driven by differences in temperature. There are three modes to transfer heat, where only conduction and radiation are fundamental and do not require a fluid in a gravity field.

The heat transfer modes are:

- **Convection:** transport of matter with different temperatures due to induced buoyant flows
- **Conduction:** diffusion of heat in a material
- **Radiation:** emission and absorption of electro-magnetic waves

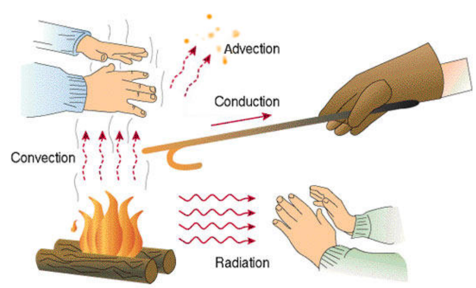

Figure 1.9: Schematic illustration of the various heat transfer modes. Source: Wikimedia Commons.

All three modes are important for fires. The released chemical energy from combustion locally heats up the gas, which changes its density and is thus affected by buoyancy. Beside the local heating, the hot gas emits thermal radiation in all directions. Thus, in case of a compartment fire, it transfers heat towards the walls or other structures, and e.g. towards the solid, which provides the fuel source for the fire. Thus, the solid's surface heats up and heat conduction spreads the absorbed energy through the solid.

1.3 Pyrolysis

Pyrolysis describes the emission of (potentially combustible) gases out of solid material. In general, this is dependent on the solid's temperature as the decomposition reactions require energy. For liquids, additional evaporation can take place.

In case of burning wood, like a match in Figure 1.10, the solid material itself is not part of the combustion, but delivers only the fuel for the fire. Not all material is gasified and a char residue is left.

Figure 1.10: Burning match, where the fuel for the combustion is emitted by the wood through pyrolysis. Source: Wikimedia Commons.