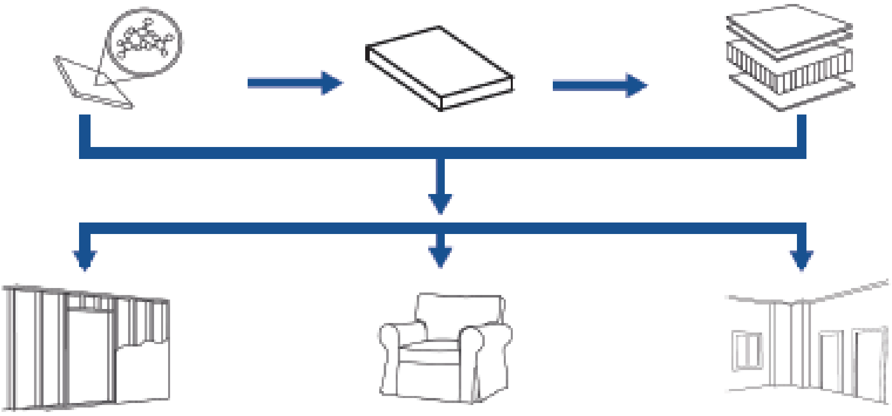
EXECUTIVE SUMMARY OF PROJECT FIRETOOLS WP R1 REPORT



27-May-14

Design of Methodology and Identification of Parameters – WP R1. Executive Summary

This document summarizes the current state of the art methodologies used in the field of fire modelling. It reviews research approaches to be used for predicting fire behaviour of materials used in building and construction industry.

Early Stage Researchers

Abhishek Bhargava:	abb@dbi-net.dk
Blanca Andres Valiente:	bav@dbi-net.dk
Frida Vermina Lundström:	fvl@dbi-net.dk
Karlis Livkiss:	kal@dbi-net.dk
Konrad Wilkens Flecknoe-Brown:	kwi@dbi-net.dk

Supervisors

Prof. Patrick Van Hees (Lund University)
Assoc. Prof. Berit Andersson (Lund University)
Dan Lauridsen (DBI)

Project Manager

Fanny Guay(DBI)

1. Introduction

The industry faces several challenges in the product development lifecycle. One of them is to pass the fire test and get an appropriate fire rating for their finished products. For this, manufacturers follow prescribed fire testing procedures laid down by the regulatory bodies. However, the very nature of the fire test is destructive, and therefore testing can be prohibitive to product development due to the high cost involved. Additionally, regular pass/fail testing doesn't reveal the product performance in 'real' fire scenarios, which may be helpful to fire safety engineers designing safe buildings using current performance-based methods.

Hence, the main aim of the FIRETOOLS project is to develop models predicting material and system fire behaviour as a function of time. Specifically the project would be focused on predicting outputs such as, temperature distributions in material, mass loss rate, heat release rate, production of toxic species and mechanical responses. The FIRETOOLS project will attempt to predict the fire behaviour of finished products (furniture, walls etc.), by understanding the behaviour of the materials, of which, they are composed. This methodology is referred as a 'multi-scale approach'.

1.1. Scope

This document is an executive summary of the literature review report done for the FIRETOOLS project. It presents a summary and the findings on the state-of-the-art in predictive modelling of fire behaviour of building contents, products and barriers. This document is intended for people with a general interest in the topic, with or without an engineering or scientific background.

1.2. Structure

The flow of this document goes from discussion of individual materials to finished product/system:

The document starts with a discussion of fire behaviour of individual materials (chapter 2). The chapter is divided in two parts:

- Physical processes modelling, which discusses material behaviour when exposed to heat;
- Pyrolysis modelling, which discusses generation of combustible gases.

Then models applied to system level are discussed; this area has been split into two different topics/chapters, which are defined by the outputs of interest (refer figure 1):

- 'Reaction-to-fire', which examines how an object will contribute to fire development (outlined in chapter 3);
- 'Fire resistance', that investigates how a structure or barrier resists the attack of fire (outlined in chapter 4).

Finally, a general summary is given, with suggestions for future work within this field of research.

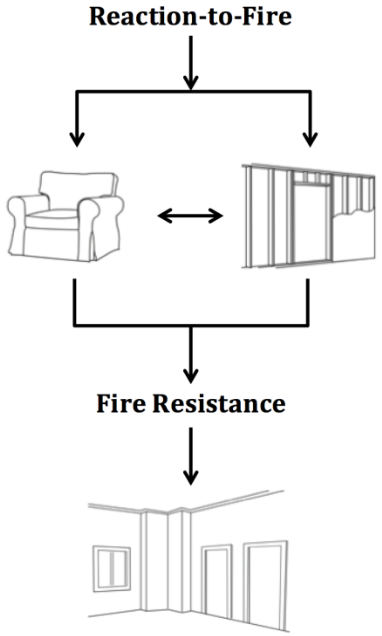


FIGURE 1 - BUILDING CONTENT AND BUILDING PRODUCTS (REACTION-TO-FIRE) CAN ACT AS INPUT (I.E. FIRE) FOR BUILDING BARRIERS (FIRE RESISTANCE)

2. Material modelling

2.1. Physical Processes in Materials

When a material is suddenly exposed to heat it loses its equilibrium state. The heat from exposed surface will be transferred into the material. The heated material may then undergo certain changes, for example: melting, expansion, cracking etc. Some of these changes will result in generation of gaseous and liquid substances which will be transferred through the solid. Thus, the heat and mass transfer must be considered in the material modelling along with physical changes mentioned before. Based on this, material equilibrium in a chosen specific location is described by the use of energy and mass balance equations (See figure 2).

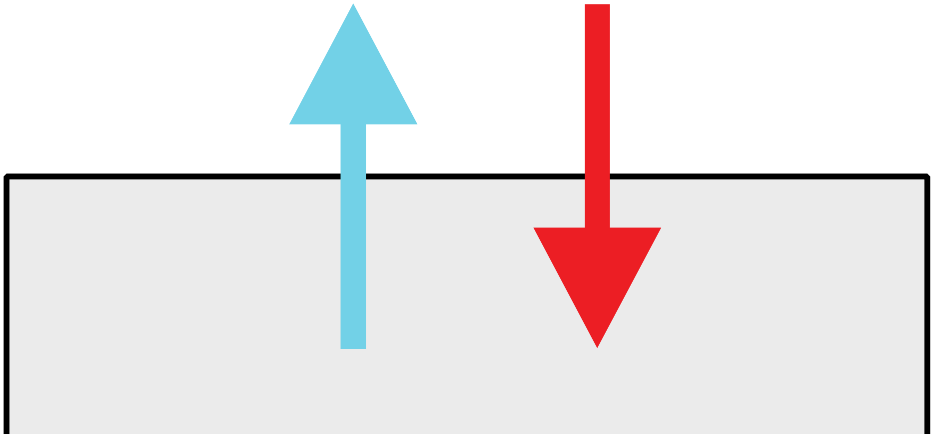


FIGURE 2 - HEAT AND MASS TRANSFER IN A MATERIAL (RED = HEAT, BLUE=MASS).

Based on the literature review within this area, issues in material modelling are:

a) Addressing and obtaining temperature dependent material properties (e.g. conductivity, permeability), which is done by material testing;
b) Addressing heat transfer by radiation and convection, which may be important in porous and fibrous materials;
c) Addressing phase changes (e.g. melting);
d) Addressing transport of gases and liquids in porous materials;
e) Addressing volumetric changes (e.g. expansion or contraction);
f) Addressing changes in mechanical properties.

Regarding to (a), researchers use the best available temperature dependent data. However data of many materials is not available or is very limited. The decision on which data is the most appropriate is left to the researcher. A common approach for (b), (c) and (d) is to adjust the model input parameters until the model predictions fit the experimental data. This approach makes models only valid for a limited range of materials (i.e. the ones, the model is fitted for). Issues (e) and (f) are usually ignored in material modelling. There are models trying to address issues (a)-(f), but seldom models consider all of them.

Until now, most modelling work has been performed with few materials (e.g. wood, steel). There is a lack of modelling attempts for a number of materials used in buildings and relevant to FIRETOOLS project.

2.2. Pyrolysis

Pyrolysis is here defined as '*the release of volatile gaseous components from the material, upon exposure to thermal attack*'. In the fire science community, this term is treated generically.

Volatile components released from a material are comprised of a mixture of gases, along with other components, depending upon the material composition. In the process of pyrolysis, the material absorbs heat and drives out volatiles due to thermal and chemical changes within the material. If the volatiles are ignited a process of combustion takes place. Combustion generates heat and can appear in the form of a flame. Consequently, the additional heat from the flame increases the production of pyrolysis gases and the fire may grow. This process is illustrated in figure 3.

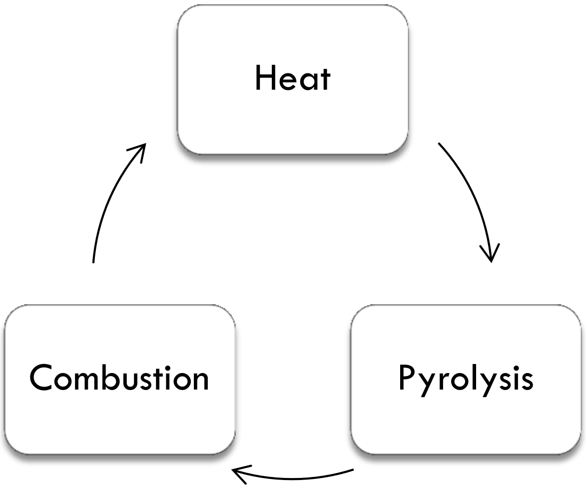


FIGURE 3. SIMPLIFIED FIRE GROWTH PROCESS

Modelling of the pyrolysis phenomenon is essential, as it influences fire growth and physical changes. Pyrolysis models are used to estimate mass loss rate, heat release rate and species production as a function of temperature and time. These parameters are critical for detailed fire modelling of any system level construction.

Models for pyrolysis can be classified into two main categories:

- Simple Thermal
- Comprehensive

In the former group, pyrolysis is described by a heat transfer model, in which the pyrolysis process is assumed to start when the temperature in the material reaches a specified level called ‘pyrolysis temperature’. This category of models does not include any physical processes, such as swelling and drying of the material. In the latter group of models, chemical reactions are taken into account and are also coupled with some physical processes. This description is closer to reality, as these processes are intrinsically linked, refer section 2.1.

The mass loss rate, which is needed to determine the heat release rate of different materials, can be described through pyrolysis modelling. There are a variety of methods to define pyrolysis of materials and they differ in complexity.

Recently, complex pyrolysis modelling software has become available, e.g. Gpyro and FireFoam. These programs use mathematical techniques, called ‘optimization schemes’, to ‘fit’ material properties in a way that model predictions match the experimental observations. For example, the user may measure mass loss rate in an experiment, and from the result received, they could then calculate, the chemical reaction properties. Then these calculated properties would be used in the model. However, when optimization schemes are used, they find ‘apparent’ (i.e. not real) material properties, which means, that they are only useful for conditions similar to the original experiment.

Although current models include some complex phenomena, there are still many unresolved issues to do with physical changes that can happen within materials.

Finished products are composed of one or more materials, and their fire behaviour may be understood by investigating the behaviour of each separate material. It can be concluded that assessing material changes and volatile release at small scale will give necessary information to develop models at larger scales.

3. Reaction-To-Fire

Reaction-to-fire in this document is defined as the analysis of a products contribution to fire growth, specifically in the early stages of fire development.

Standard reaction-to-fire testing predominately investigates fire behaviour in the compartment of fire origin. When considering reaction-to-fire, the phenomena that should be considered important for various materials include:

- Heat release rate
- Ease of ignition
- Flame spread (across and between items)
- Smoke production
- Toxicity

Both building content and building products are categories that have statistically shown to be some of the most common sources of fire initiation (i.e. first item ignited) and in most cases are the largest contributors to fire growth within a compartment. Thus, both are relevant when discussing reaction-to-fire. Moreover, they also interact with each other during fire growth. *Building content* refers to mobile objects that are placed within a building. Some examples of building content may include furniture, electrical equipment or other movable internal furnishings. A *building product* is defined as a non-movable object that is used in the construction of a room or building. Examples of building products are wall- and ceiling linings, floor coverings and non-movable installations. Building content and building products are usually a composition or assembly of numerous materials and hence, the interactions between various materials are of prime importance when considering the fire behaviour of items in the above categories.

The various methods that have been employed previously in attempting to develop a prediction methodology for the fire behaviour of building content and building products have been divided into three categories:

- Empirical Models
- Thermal-Limited Models
- Comprehensive Models

The first category, designated 'Empirical' is due to the methodology employed in the development of these models. This methodology is based on the statistical analysis of experimental data to extrapolate predictions for items/materials analogous to those analysed during the experimental phase. The second category, here named 'Thermal-Limited' include those models that have attempted to integrate some form of heat transfer theory within their modelling approach. The last category, 'Comprehensive', refers to models that take more fundamental processes into consideration, e.g. chemical reaction rates.

On review of many full-scale models within the area of reaction-to-fire, it was found that the majority of methodologies predominately aimed to predict the heat release rate, and were based on empirical data and correlations. However, all models reviewed included certain empirical factors in some form, to take into account phenomena that were not specifically modelled. The thermal-limited and comprehensive methodologies introduce more material specific properties as inputs to the models, making these models more generalizable and more pertinent to other applications than the intended/validated items. Nonetheless, increasing the number of input variables also raises issues regarding potentially higher levels of uncertainty.

This brings the conclusion that; a model that can predict results with reasonable accuracy when applied to numerous material combinations and configurations is still out of reach. Moving forward, if we are to produce more generalised prediction methodologies in which we can predict full-scale fire growth within a compartment, there is a need for greater knowledge in two major areas. These areas being: (1) greater understanding of material behaviour at a 'fundamental' or micro-scale level and, (2) an increased knowledge of both environmental effects, and the effects of scaling (going from small specimen of material to a full construction).

Recent authors are making headway into understanding material behaviour at the smaller scales. Although there are still many phenomenological considerations that require further investigation. Examples of this include:

- Temperature dependent material properties
- Phase change (e.g. melting)
- Material interactions
- Mechanical failures
- Structural (e.g. frame) collapse
- etc.

On top of these, the number of phenomena that needs to be considered also increases with increasing scales. For instance, in micro-scale measurements, temperature gradients are often neglected and the experimenter can choose both atmospheric conditions and heating rate. In larger-scales, temperature gradients may no longer be neglected, environmental conditions depend on numerous variables e.g. openings, room geometry etc. Material heating rates are governed by the flame itself, radiation from other burning objects and the hot gas layer. This means, that heating rate and atmospheric conditions are no longer controlled by the experimenter, thus it's much more complicated to understand large-scale tests.

Based on this, there is a need for coupled models that can take into consideration both material behaviour and environmental influences if we are to develop prediction methodologies that can be applied to full-scale scenarios. At the moment, validating the modelling methodologies at intermediate steps is necessary. Hence, a multi-scale modelling approach is a way forward.

Reaction-to-fire modelling may also act as a means of input into the other topic of this document, namely, 'fire resistance' (refer Figure 1).

4. Fire Resistance

Fire resistance is the ability of a certain element or system to maintain its function when exposed to a fire. The fire performance of the building constructions will determine spread of the fire in the building and available egress time for occupants.

A building barrier is defined as a separating element designed to restrict the spread of fire and smoke to adjacent spaces. Numerous experimental studies and attempts to model the resistance to fire of building barriers have been carried out, since a better understanding on their behaviour would lead to safer and more economic buildings. Standard testing of fire barriers has been performed to assign certain classification. However this practice has been anchored to test constructions in a non-real fire scenario, which provides poor knowledge on building barriers performance in real fires.

Modelling the fire behaviour of building barriers should include as accurately as possible, all the phenomena taking place in order to foresee the fulfilment of the insulation, integrity and structural stability criteria by which building barriers are judged. A complete approach would include:

- Fire model,
- Thermal model,
- Degradation of the mechanical properties as a function of time
- Thermal deformations
- Material model
- Structural model

The majority of the models reviewed (i.e. steel doors, glass assemblies, gypsum board assemblies, sandwich panels and cross laminated timber) have been focused on the prediction of the heat transfer through the building barriers without tackling other phenomena i.e. falling-off, burning through and opening of joints. These models, although accurate in their range of application, fail to predict fire resistance when discounted phenomena become part of the main failure mode.

Therefore more generalized models capable of predicting fire behaviour in different scenarios are still to be developed. A multi-scale approach in which the behaviour of the materials at small scale can be extrapolated to higher scales is a possible way forward.

5. Conclusions

The task of modelling fire behaviour of materials in its entirety is exceedingly complex; the physical and chemical interactions between the materials and environment are intimately linked and 'real' items often display a multitude of phenomena. Hypothetically, an accurate model would use only fundamental physical laws. In practice, a purely fundamental model is not feasible at this time. This is due to the current computer modelling limitations and existing knowledge of processes occurring in materials. These processes are extremely complex and many of them are intrinsically linked i.e. depend on each other. Understanding physical and chemical processes will provide better input for modelling.

In summary, the shortcomings and gaps (i.e. potential for future work) in existing modelling work include:

- Lack of robust thermal and mechanical material property data at high temperatures;
- Lack of knowledge on the performance of materials at elevated temperatures and difficulties of modelling certain processes;
- Lack of understanding the heating conditions in tests, especially if large tests are performed;
- Materials behave differently when exposed to standard fire tests or to real fire conditions;
- Very few validation studies has been performed for developed models;
- Sensitivity studies (investigation on what effect input parameters have on the model output) are seldom performed.

With these issues in mind, future work regarding the FIRETOOLS project will focus on more in-depth studies of certain important processes that take place in fire conditions: heat transfer, combustion properties, chemical kinetics, phase transfer and mechanical properties. Understanding these processes will provide needed knowledge for material and system modelling.