Risks in using CFD-codes for analytical fire-based design in buildings with a focus on FDS:s handling of under-ventilated fires

Anders Björklund

Department of Fire Safety Engineering and Systems Safety
Lund University, Sweden

Brandteknik och Riskhantering
Lunds tekniska högskola
Lunds universitet

Report 5281, Lund 2009

Risks in using CFD-codes for analytical fire-based design in buildings with a focus on FDS:s handling of under-ventilated fires

Anders Björklund

Lund 2009

Title
Risks in using CFD-codes for analytical fire-based design in buildings
with a focus on FDS:s handling of under-ventilated fires.

Titel
Risker vid användandet av CFD modeller i analytiska dimensioneringar
i byggnader med fokus på FDS hantering av underventilerade bränder.

Author/Författare
Anders Björklund

Report 5281
ISSN: 1402-3504
ISRN: LUTVDG/TVBB--5281--SE

Number of pages: 131

Key words: CFD, FDS, combustion, under-ventilated, fire, uncertainty, validation, simulation, usage, reviewer, risks.

Sökord: CFD, FDS, förbränning, underventilerad, brand, osäkerhet, simulering, användande, granskare, risker.

Abstract

The use of computational fluid dynamic (CFD) models is common as an engineering tool for fire based analytical design of buildings. To avoid incorrect fire safety design it is important that the computer modelling and its process are performed in a good way i.e. performed in such a way that incorrect fire safety design in buildings is minimized. In this report, it is investigated if possible incorrectness in how the CFD-program FDS simulates under-ventilated fires can constitute a risk for incorrect fire safety design in buildings. This is investigated by doing a validation study of FDS but also by checking how the users and the reviewers handle the program especially concerning under-ventilated fires. The validation study is done by comparing FDS output with experimental tests performed by the SP Technical and Research Institute of Sweden. How the program is handled by its users and reviewers are done via telephone interviews.

The results show that FDS has problems of simulating the conditions in an under-ventilated fire correctly. This is much dependent on the empirical expression for when the fire is allowed to burn but also the limitations of the mixture fraction combustion model. The program can therefore create unconservative results concerning the temperature, the visibility and the toxicity (carbon monoxide). The telephone surveys show that the users and reviewers generally have a relatively good understanding about CFD but that they lack in knowledge when it comes to how FDS treats under-ventilated fires. In total it is likely that the incorrectness in how FDS simulates under-ventilated fires results in incorrect fire safety design in buildings a few times a year in Sweden.

Brandteknik och Riskhantering
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Department of Fire Safety Engineering
and Systems Safety
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se/english

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

Contents

Preface

This report is the final examination work for the Fire and Safety Engineering programme and Risk Management and Safety Engineering programme given at the Department of Fire and Safety Engineering and Systems Safety at Lund University.

During the work many people have helped me and I want to thank my supervisors Anders Lönnermark at SP Technical Research Institute of Sweden and Patrick van Hees at the Department of Fire and Safety Engineering and Systems Safety (Lund University). I also want to thank Göran Holmstedt of the Department of Fires and Safety Engineering and Systems Safety (Lund University) for all his help with questions concerning FDS. I want to thank my examiner Håkan Frantzich at the Department of Fire and Safety Engineering and Systems Safety (Lund University). I want to thank Heimo Tuovinen at SP Technical Research Institute of Sweden for his help with the computer cluster at the University Collage of Borås.

Finally a want to thank my family, my children Noah and Alva for keeping me happy during dark times and to Mirja, without her this report would never have been finished.

Sammanfattning

Användandet av CFD modeller som ett hjälpmedel för ingenjörer i analytiska dimensioneringar har under de senaste åren ökat. Anledningen till detta är dels att lagstiftningen tillåter analytisk dimensionering men också genom att den ställer högre krav på verifiering. Den största anledning är dock att datorkraften har ökat och nått den gräns där det är ekonomiskt och tidsmässigt försvarbart att använda CFD-modeller för konsultändamål. I Sverige är det vanligaste CFD-programmet FDS (Fire Dynamics Simulator) vilket utvecklas av NIST (National Institute of Standards and Technology), dagens version är den femte programversionen. För att säkerställa att programmet gör en så korrekt beskrivning av verkligheten som möjligt behöver den valideras gentemot försöksdata. I denna rapport valideras FDS för underventilerade bränder. Det är dock inte endast hur programmet beskriver verkligheten som skapar risker utan även hur programmet används av sina användare samt deras granskare. Om felaktiga resultat används på ett felaktigt sätt kan detta innebära att brandskydd i byggnader dimensioneras på ett felaktigt sätt vilket kan ha en negativ påverkan för personers utrymningsförhållanden vid en brand.

Processen för att avgöra om felaktigheter i hur FDS simulerar underventilerade bränder genomförs i fyra steg. Först beskrivs när och hur underventilerade bränder uppkommer samt vilka konsekvenser de kan ha för personers hälsa vid brand, något som görs via litteraturstudier. Nästa steg är en validering av hur FDS hanterar underventilerade bränder vilket genomförs genom att jämföra utdata från FDS med experimentella testdata från av SP Sveriges Tekniska Forskningsinstitut. Testen är en del av ett större forskningsprojekt (BRANDFORSK) finansierat av Styrelsen för Svensk brandforskning. Nästa steg är att avgöra huruvida användningen av FDS, vid underventilerade bränder, sker på ett bra sätt. Detta genomförs genom att brandskyddskonsulter i Sverige telefonintervjuas. Nästa steg är att undersöka hur den granskande parten (oftast räddningstjänstförbund) klarar av sin roll som granskare i avseende på kunskap och resurser, något som också genomförs via intervjuer.

Resultaten visar på att det empiriska samband i FDS som beskriver när det tillåts brinna samt begränsningar i förbränningsmodellen gör att resultaten vad gäller temperatur är mycket känslig för skillnader i syrehalt, vilket gör den svår att tillämpa på ett bra sätt. Sikt och toxicitet som främst baseras på sot och kolmonoxid yielder är betydlig svårare att tillämpa och användning av dessa utdata parametrar bör ske med stor försiktighet. Resultaten ifrån undersökningen om hur användarna hanterar FDS för underventilerade bränder visar att användarna överlag har dålig kunskap om hur FDS fungerar vid underventilerade bränder men att användningen av basfunktioner i FDS sker på ett bra sätt. I undersökningen om vad för kunskap samt vad för kapacitet räddningstjänstförbunden har för att genomföra en bra granskning av analytiska dimensioneringar där underventilerade bränder ingår, är det tydlig att de saknar både kunskap och resurser för att genomföra en bra granskning. Totalt sett innebär detta att brister i hur FDS simulerar underventilerade bränder utgör en risk då det används som underlag för dimensionering av en byggands brandskydd. Konsekvensen är att personer som befinner sig i bygganden kan utsättas för förhållanden som är farliga (i större grad) för deras hälsa vid en eventuell brand.

Åtgärdsförslag för att minska riskerna är att t.ex. att CFD kursen som ges av Brandteknik på Lunds Universitet i större grad skall innefatta hur FDS hanterar underventilerade bränder samt hur utdata påverkas. Detta är dock ingen garanti för att studenterna/användarna faktisk lär sig mer utan det bör även instiftas en certifiering av CFD/FDS kunniga användare/konsulter. En lämplig certifieringsgenomförare är då helst en branschförening som t.ex. BIV. Det är även lämpligt att förbättra förutsättningar för räddningstjänstens granskning.

Summary

The use of CFD-models as an engineering tool for fire based analytical design of buildings has increased over the last few years. The reason for this is partly that the legislation allows for analytical dimensioning but also because the legislation demands a high degree of verification for the analytical dimensioning. The biggest reason is, however, that the computer power has increased and reached a point where it is applicable for engineering problems in terms of both time and money. The most common CFD-program in Sweden is FDS (Fire Dynamics Simulator) which is developed by NIST (National Institute of Standards and Technology), today's version is the fifth large release. To ensure the correctness of the program it needs to be validated against experimental data. In this report, FDS is validated for under-ventilated fires. It is, however, not only how the program simulates the reality that is associated with risks but also how the program is handled by its users and their reviewers. If incorrect results are used and reviewed in an incorrect way that means that fire safety design in buildings may be incorrectly dimensioned which can have a negative impact on people's health during evacuations in case of fire.

The process to decide if incorrectness in how FDS simulates under-ventilated fires is made in four steps. First, under-ventilated fires are described, how and when they arise and what consequences they may have for people's health during fires, which is made through a literature study. The next step is to validate how FDS works for under-ventilated fires, which is made by comparing FDS output data with experimental tests performed by the SP Technical and Research Institute of Sweden. The test is a part of a larger research project (BRANDFORSK) financed by the Swedish Fire Research Board. The next step is to decide how the users handle under-ventilated in FDS. This is done through a series of telephone interviews with fire and safety design consultants in Sweden. The fourth step is to investigate how the reviewer (rescue services) handles their role as a reviewer.

The results show that the empirical expression concerning when a fire is allowed to burn or not together with the mixture fraction combustion makes the heat release rate and thereby the temperatures very sensitive for changes of oxygen level. Visibility and toxicity (carbon monoxide level), which is based on the soot and carbon monoxide yields, are much harder to apply and the FDS output for these parameters should be used very cautiously. The results also show that the fire and safety design consultants generally have little understanding about how FDS treats under-ventilated fires but that the basic use is handled in a good way. It is clear that although the rescue services in many cases can do a good review of an analytical dimensioning, they lack the knowledge and the resources for doing a good review of an analytical dimensioning with an under-ventilated fire involved. In total this means that incorrectness in how FDS simulates an under-ventilated fires do constitute a risk when it is used in analytical dimensioning of a buildings fire and safety design. The consequence can be that people in the building may be exposed to conditions dangerous (in a higher degree) to their health.

Measures to reduce the risk are for example that the CFD course given at the Department of Fire and Safety Engineering and Systems Safety at Lund University contains more elements about how FDS handles under-ventilated fire and how the output is affected. This is however no guarantee for that the students/users actually learn more and there should also exist certified CFD/FDS able users. A suitable party for this is a trade organisation like BIV. It is also appropriate to improve the conditions for the rescue service in their reviewing role.

1 Background

The building legislation in Sweden has changed from being prescriptive to become more performance based. This means that the building code requirements also can be verified by an analytical solution instead of just following prescriptive guidelines. There is also a tougher climate in building business where the future proprietor (Byggherre) has to be as economically efficient as possible. To build smart can save a lot of money and for fire safety design that often means analytical solutions. In the Swedish buildings codes (Boverkets byggregler) it is stated that analytical solutions has to have a higher degree of verification compared to just following the building codes or recognised handbooks (Boverket 2008). In analytical solutions, e.g. an evacuation dimensioning, the use of computer programs for simulating the heat and smoke spread is common. In recent years a group of computer codes named CFD (Computational Fluid Dynamics) has emerged as an engineering tool for describing smoke spread.

When an analytical dimensioning is the case in building project it is up to the future proprietor to ensure that the fire safety standards are met (9 chapter 1 § PBL). The future proprietor usually lay this task upon the fire and safety design consultants internal quality checks (egenkontroll) although the responsibility still lie with the future proprietor. The local building board (Byggnadsnämnden) is responsible for the municipal's tasks within construction (1 chapter 7 § PBL) and at the building consultation meeting they decide whether or not the future proprietor's control system (in this case the level of control) is sufficient. If local buidling board is not capable (almost always) of making that judgement they may use a referral instance which most often is the fire and rescue service. The purpose is not that the rescue service should be a second dimensioner but just suggest the level of control that is needed. In recent years it has, however, been acknowledged some serious shortage in the future proprietors internal checks (Lundin 2005). Many rescue services have therefore expanded their role and do often stand as an unofficial quality checker of analytical dimensionings.

The computer program that is validated in this report, FDS (McGrattan 2008), is to some extent verified and validated (see section 4.1 for definition) by its developer (National Institute of Standards and Technology – NIST). Despite this, there are many functions and models in the program that are linked with uncertainty and error. In FDS one of these models, the mixture fraction combustion model, is linked with both uncertainties and errors when used for under-ventilated fires.

It is, however, not only the correctness of the program that is a source of error and uncertainty, but also how the program is managed by its users. In Sweden, CFD and FDS is mostly used by fire safety consultants that work for consultancy agencies. The use of CFD and FDS has increased in recent years which is linked to the development of computer power. Since further development in computer power is inevitable, the use of CFD and FDS will increase even more in years to come.

The fact that error and uncertainty exists in the computer modelling creates a possibility for that incorrect dimensioning will lead to hazards for people's safety in buildings in case of a fire. Therefore it is necessary to manage the risks i.e. it is necessary to use the program in such a way that eventual error and uncertainty in the program does not affect the fire safety design in a building in a "negative" way.

When it comes to validation of CFD a large validation and verification study of most of the models included in FDS has been done on initiative from the US Nuclear Regularity Commission (U.S.NRC. 2007). The study is a serie of 7 reports where one of them, volume 7, concerns FDS. In the report FDS 4 was used but covers most of the models included in FDS 5. It does not focus especially on under-ventilated fires even though some of the experiments that were compared against reached under-ventilated stages. Some of the results concerning the oxygen level (important for under-ventilated fires) for the under-ventilated fires are even questioned by the writers themselves who cannot find an explanation for the results. Simulation of under-ventilated fires has also been done by Heimo

Touvinen (Touvinen 1996) but the progam used in that report was SOFIE (Simulation Of Fires In Enclosures) (Rubini 2006) which is based on a RANS-code (see section 8.2).

When it comes to risks related to the use of CFD the previous work really consist of a wide spread theory that it is the user handling that stands for the biggest risk, see for example "*An introduction to CFD*" (Rubini 2008).

2 Objectives, Purpose and Goals

On the basis of the background information above several problems related to the use of CFD and FDS models, are obvious. In this report the following problems and risks are examined.

- How does FDS simulate an under-ventilated fire?
- Does possible incorrectness in how FDS simulates under-ventilated fires constitute risks of incorrect fire safety design in buildings?
- What can be done to reduce the risks?

A part of this report is a validation study and a validation study can have many different goals or purposes. The goal in this report is to try increase the understanding of how good FDS simulates under-ventilated fires. The goal is on a risk management perspective which means that the purpose is to try and improve the handling of the program and the process and not to improve the code itself.

3 Limitations and Terminology

Only CFD use for smoke spread will be addressed although CFD is used for a variety of applications e.g. weather prediction and dust explosions. In this report only FDS is validated against the experimental data although there exists many different CFD programs. FDS is chosen because there are reasons to believe that FDS is the most common CFD-program for smoke filling used amongst fire safety design consultants in Sweden. In FDS only "standard" models are used and sub models such as flame spread is not involved. The reason for this is because many of the "none" standard sub models are still at a research level and will only bring more uncertainties and errors into the calculations.

The risks associated with the use of FDS for fire safety design in buildings will only be mapped for users in Sweden. Whether or not it represents the usage in other countries is not investigated.

The presentation of the output data from the SP test is limited. The total amount of data can be viewed in *"Smoke spread and gas temperatures during fires in retail premises – Experiments and CFD simulations"* (Lönnermark & Björklund 2009). The information concerning the experiments that is presented here can be seen as an abstract.

The goal is not to perform a complete quantitative risk analysis but only to enhance an highlight areas associated with risks for incorrect analytical fire based design in buildings (related to the use of under-ventilated fires in CFD) and to a certain degree try to measure the possibility and the consequences of the risks in a qualitative way.

There is no attempt to decide what an acceptable risk level is.

Under-ventilated fire and ventilation controlled fire are used as synonyms.

The word dimensioning is used to describe the analytical process of which the CFD simulation is a part. The word design describes the final fire safety design in a building.

The term test is used to describe the test 1-11 and the term case is used to describe the simulated tests.

4 Validation, Error, Uncertainty and Risk

4.1 Validation

Since a validation of FDS for under-ventilated fires is a part of this study it is appropriate to define what a validation is. Validation and verification are two words that often can be taken for synonyms of each other. In *"Credible CFD – Verification and Validation*" (Rubini 2008a) they are defined as follows:

Validation – *"The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model".*

Verification – *"The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model"*

Or in other words a validation checks that the right equations are solved and verification checks that the equations are solved in the right way.

Why should a validation be done and how is a good validation performed? A validation creates confidence and credibility, the process also makes it easier to quantify error and uncertainty.
In the standard E 1355-05a*"Standard Guide for Evaluating the Predictive of Deterministic Fire Models"* (ASTM 2005) the evaluating process of fire modelling is described. The standard splits up the evaluation process into four different parts or processes. The first process is to define the model and scenarios for which the evaluation is to be conducted for. The second is to verify the appropriateness of the theoretical basis and assumptions used in the model. The third is to verify the mathematical and numerical robustness of the model. The fourth is to quantify the uncertainty and accuracy of the models results in predicting events of similar fire scenarios.

In this report the goal is not solely on the validation but on managing the risk related to the possible incorrectness in the code. Therefore, the first two steps will only be done to a certain depth, the third step will be left out but the forth step will be done thoroughly. The reason for leaving the some of the theoretical basis and the mathematical robustness is done because of the goal on this report, see chapter 2, but also that this is up to the developer (NIST) since it is necessary to go in to the code to be able to measure the mathematical robustness. Depending on the purpose of the validation it can be performed in different ways. The methods can be to examine the equations and the source code to see if they are "correct" or the simulations can be compared to experimental data. The latter hardens the process of finding the actual error in the equations or in the programming. It gives, however, a direct estimation of how the program actually simulates the reality. Which method that should be used must be put in to relation to what the goal is. Is it to further develop the code, so that it in the future may simulate a problem in a better way? Then a close examination of the equations might be the right way. Is the goal to increase the current usage then comparison with experimental data can be a good way.

4.2 Error, Uncertainty and Risk

In the validation the terms error and uncertainty are frequently used and the difference needs to be clarified. In *"Credible CFD – Verification and Validation"* (Rubini 2008a) they are defined as follows:

Uncertainty – *"A potential deficiency in any phase or activity of the modelling process that is due to the lack of knowledge"*

Error – "*A recognisable deficiency in any phase or activity of the modelling process that is due to the lack of knowledge"*

Or in other words "in" uncertainty there may exist a deficiency (but not for sure), while the deficiency "in" an error is known.

The difference between uncertainty and risk can also be vague and needs to be clarified. Error and uncertainty may create incorrect results and when used for fire safety design in buildings it may lead to incorrect design. The incorrect design may create hazardous circumstances in the building in case of fire. The fact that error and uncertainties can occur and can have negative consequences on a buildings fire safety design can be defined as a risk. In this report there is no attempt to measure the risks in a quantitative way but instead in a qualitative way. Because of that, when the term risk is used in this report it means the probability of that a deficiency (error or uncertainty) can occur which can lead to consequences that can create hazardous circumstances for people in buildings in case of a fire.

4.3 Experimental and computer modelling uncertainty

It is not just computer modelling that are associated with uncertainty and error. The experimental results are also linked with uncertainty and errors. The measuring of the reality can never be an exact representation of the real world. It can be that the measuring devices affect the surrounding, but on this level of measuring the biggest source of error and uncertainty is that the devices are "too incorrect". A thermocouple has for example some thermal inertia which is dependent on the thickness of the material, a light beam sent out from a laser is dependent on how clean the lamp is, an oxygen reader has to be calibrated correctly etc.

The error or uncertainty factor must of course be put into relevance, in some cases a temperature difference of 5 ^{o}C is much and in other cases it might be insignificant. What an acceptable difference is has to be decided for each case. It is hard to quantify the differences between the measured reality and the actual reality but by using different measuring devices, the error or uncertainty factor can be quantified to a certain level. In the SP tests the temperature is for example measured with thermocouples with different thickness which gives an indication of the magnitude of the error factor, for further information about experimental uncertainty in this context see for example *"Verification and Validation of Selected Fires Models for Nuclear Power Plant Applications Volume 2: Experimental Uncertainty"* (U.S.NRC 2007b) .

The question of how a good validation of a computer program should be done was raised above where a comparison between experimental results was brought up as a possible way. When deciding how good the match is between the two, the differences are measured. But how does one decide where to draw the line for a good resemblance? First there is problem with the "combined uncertainty". Since both the computer model and the experimental tests are associated with errors and uncertainties it makes the comparison harder. If for example the measuring devices records the temperature 10 ^{o}C higher than the actual reality and the computer model predicts 10 ^{o}C lower than the reality, then the difference is 20 ^{o}C while it really is 0 ^{o}C. This hardens the process and to deal with this the scenario should be run for several different set ups. Because of lack of experimental tests this is not often a possibility and one has instead to try to estimate each of the different error and uncertainty factors by doing sensitivity analysis on possible factors.

A second problem is that some averaging usually is needed to be able to get a picture of overall change, but by “altering” the results the actual difference becomes smaller or bigger then it originally was. Averaging the results it also hardens the any attempt to identify different parts of the scenario, it might be that different parts may require different averaging for a good presentation. Any averaging therefore has to be done on an appropriate scale.

Another problem is that of the difference between actual difference and percentage difference. If for example the computer output show 30 °C and the experimental output show 15 ° C then the difference is 15 °C or 50 %. If one were to try and apply these numbers on a different scenario with much higher temperatures, should the difference in real numbers or in percentage be used? (NB that the percentage difference decreases with higher temperatures or also if they thermal scale would have been given in Kelvin). This is easily dealt with by doing comparison for different levels of the output i.e. the temperature in one experiment may be significantly lower or higher then in another.

Since the validation in this report focus on the overall treatment of a model and not the exact function of for example the source code for under-ventilated fires, more factors that can affect the results are brought into “play”. It might for example be something else then the combustion model that creates the results, it might be the geometry, grid resolution etc. This can be examined by thorough sensitivity analysis but only to a certain extent, it is not possible to test all the including functions. A work frame of trying to decide which sensitivity analyses that are appropriate are by looking at the goal. In this case to try and include the different factors that can have an effect it its normal use, amongst the fire safety design consultants e.g. grid sensitivity, different mesh build-ups etc.

5 Method

The method for trying to asses if possible incorrectness in how FDS simulates under-ventilated fires constitute a risk of incorrect fire safety design in buildings is done via a event tree "methodology". The different branches in the tree are meant to be the different steps or important parts of a real dimensioning process. It is, however, no quantitative event tree methodology and the event tree is really just scheme to identify and organize the different events that can result in incorrect fire based design in buildings. The first branch is to identify where and when under-ventilated fires happen and how often they are simulated. This step will give information about both the consequence and to a certain degree the possibility of the risk. The second branch is to examine how FDS simulates under-ventilated fires. This information will define what can go wrong (risk scenario) and to a certain degree the magnitude of the consequence. The third branch is to examine the users handling of the program and its input and output for under-ventilated fires. The forth link is to examine what the reviewers knowledge is, if they are qualified of doing a good review. The third link gives information about the consequence and possibility and the forth step about the possibility of the risks.

The method for identifying where and when under-ventilated fires happen and how often they are simulated is done via literature studies and interviews. When trying to estimate how often under-ventilated fires are simulated, fire safety consultants in Sweden are contacted, see chapter 9 for more information about the survey.

A validation is performed to answer the question about how FDS simulates under-ventilated fires. This is done by comparing the experimental results (the SP tests) with FDS output data. To be able to perform the comparison the experimental data is first reviewed and summarized. The test that showed clear signs of being under-ventilated are then simulated in FDS along with a well-ventilated reference scenario. The method of deciding on how well FDS simulates under-ventilated fires is partly done by trying to estimate the error and uncertainty in the experimental results as well as in FDS. These two factors lie as basis for quantification of the difference between the FDS output and the experimental results. The error and uncertainty factors in FDS are dealt with trough sensitivity analysis. This does not go to the bottom of the eventual error but it narrows in or lessens the quantity of it. The error and uncertainty factors in the experimental results will be treated through comparison between repeated experiments and different measurement of the same parameter.

In the step where the users handling of under-ventilated fires in FDS is examined interviews are done with fire and safety design consultants in Sweden, the base questions can be found in appendix A. The interview technique is described below but followed the guidelines in *"Vetenskaplig metod"*(Ejvegård 2007). Once the interviews actually took place further questions sometimes aroused which led to that information was gathered outside the frame of the interview sheet. The survey is linked with several uncertainties e.g. are the right questions asked, are they asked in good way, are the right people interviewed and are they telling the truth? First, the identification and assessment of the possible risk do not cover all aspects of the use of CFD and FDS which narrows down the relevant questions. The method of asking the questions in a right way is approached by trying to not ask leading questions but instead try to ask "open" questions. The problem of asking the right people is dealt with by asking both big and small companies. Within the companies it was mostly the FDS supervisor or the most FDS able person that was interviewed, but employees with lesser experience were also interviewed. To make the respondents to talk the about the true usage they were guaranteed that neither their name nor their companies name would be mentioned in the report. To be able to draw some conclusion about the possibility of an incorrect dimensioning the answers are transformed to simple statistics.

The forth link is to evaluate the reviewers capability to perform their review of an analytical dimensioning with an under-ventilated fire simulated in FDS. This is done in the same way as with the users, an interview survey, but the interviewed persons are instead employees at the Swedish rescue services.

In the end it will be known what can happen when FDS is used for under-ventilated fires (risk-scenario) what the consequences can be and how likely they are to happen. The final “sum up” will not give a certain value of the risk but instead a qualitative estimation.

6 The Event Tree

The process of identifying the possible risks related to the use of CFD and FDS for under-ventilated fires in fire safety dimensioning is, as mentioned above, done with an event tree methodology. The tree is not intended to be used as a tool for quantification of possibility and consequence but merely a tool for describing the events that lead to incorrect fire safety design in buildings. Each section of errors is investigated, these error sections are the branches of the event tree below. Each error section is described in short in this chapter and then more thoroughly in the following chapters.

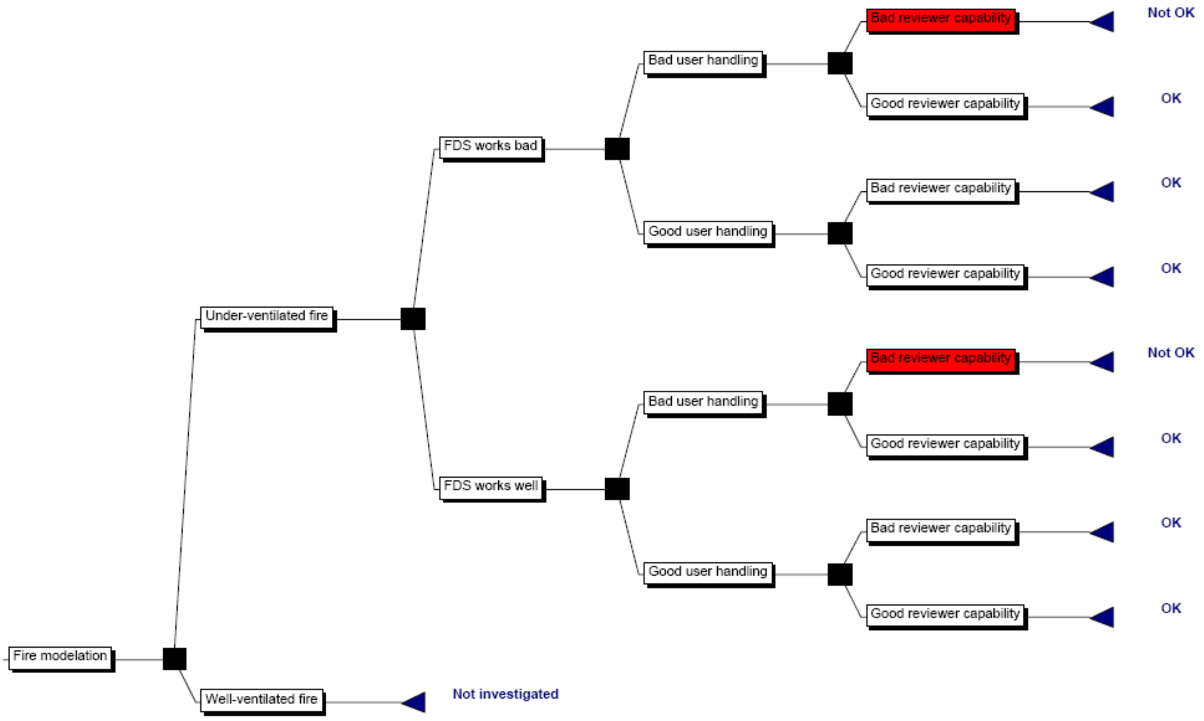


Figure 6.1: The event tree.

The starting point “Fire modelling” is introduced when an analytical fire safety design of a building needs to be verified.

The well-ventilated fire branch is not investigated and therefore deleted. In the end of the tree there are two types of values: OK or Not OK. OK means that the scenario, i.e. the series of events, does not constitute a risk for that incorrect design in buildings occurs. This means that even if the FDS works bad for under-ventilated fires it might still be “OK” if the users or reviewers handles it in such a way that eventual errors does not lead to incorrect fire safety design in buildings. Not OK is the opposite i.e. a series of events that can lead to incorrect design in buildings.

Under-ventilated fires

When under-ventilated fires happens and how often they are used as a dimensioning fire in a CFD simulation is vital since this lie as a basis for how often incorrect fire safety dimensioning can occur, due to the problem at hand. If under-ventilated fires are so rare that it practically never occurs or if it is seldom simulated then the related risks are also small.

How does FDS simulate under-ventilated fires?

How FDS simulates under-ventilated fires is a basic condition for the risks related to the use of FDS for under-ventilated fires in fire safety dimensioning. If FDS simulates it in a good way then the possibility of an error in some of the later stages, such as the user’s handling, is lowered.

User handling

How the user handles the program, the working process and the results are very important. Even if the program would simulate under-ventilated fires in a good way the user may still make poor assumptions or interpret the output in a bad way.

Reviewer handling

If the results from the simulation are reviewed and if so how they are reviewed are also very important. If incorrectness has occurred in the earlier stages of the modelling process it might be detected in the review, which lessens the possibility of incorrect dimensioning of a buildings fire safety design.

In the following chapters each step is investigated but if for example “FDS works bad” is true then “FDS works good” branch is not further investigated.

7 Under-ventilated fires

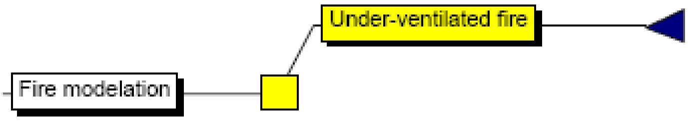


Figure 7.1: First branch of the event tree.

Under-ventilated fires often arise in at least three types of scenarios (Lönnermark 2008). In enclosures with no or small inlet and outlet openings where the oxygen level can start to fall quickly dependent on the size of the enclosure. A typical enclosure is a storage or supply room. This can also be a dimensioning fire in an analytical dimensioning. The reason for this is that it is likely that the storage room is equipped with a detector which is activated when the fire starts, the fire builds up and enters a ventilation controlled stage. When personnel come to check the alarm the unburned gases can swiftly spread into the bordering room and cause a rapid fire development.

The second typical scenario is a room or enclosure with a low ceiling height compared to the heat release rate. If the flames are positioned in the smoke layer then the fire will get ventilation-controlled, this can be the case for many buildings e.g. office buildings.

Another kind of under-ventilated fire is where there is a really big fire when the oxygen can not reach the fuel source since there is lot of unburned gases surrounding the fire. This means that an under-ventilated fire may occur even in big volumes.

In under-ventilated fires the soot and carbon monoxide -production is much higher then in a well-ventilated fire (Tewarson 1995). This together with that about two thirds of the deaths in fire is related to the poisoning by carbon monoxide (Tuovinen 1996) makes it very important to try to estimate the concentrations correctly when used in an analytical dimensioning. The consequence can be high since incorrect dimensioning directly affect the possibility of that peoples lives are threatened.

If then under-ventilated fires happen and can be a dimensioning fire, when is it simulated by the FDS users? Through the survey it is clear that some agencies simulate under-ventilated fires quite often and that some never simulates it. Even if the users do not use an under-ventilated fire as a dimensioning fire it might still be an under-ventilated fire without the user knowing it. In the survey it is also clear that most of the consultants do not now how FDS treats under-ventilated fire and that many does not check the heat release rate output which quickly gives a hint about the degree of ventilation controlled fire.

Conclusion
Incorrect dimensioning of under-ventilated fires can have a big consequence since it has a big impact on the carbon monoxide and the soot yield which are strongly correlated with toxicity and visibility. The possibility of that an under-ventilated fire is present in a simulation or in a “real fire” is probable to happen a few times a year (in Sweden).

8 Validation of FDS for under-ventilated fires

In this step it is investigated how FDS work for under-ventilated fires.

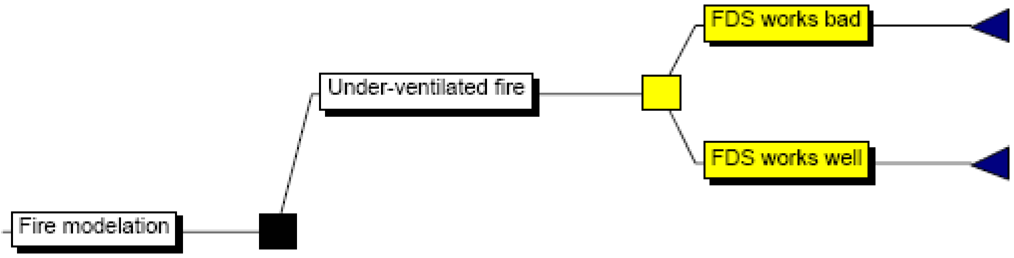


Figure 8.1: Second branch of the vent tree.

Before dealing with the validation there are some introducing sections about simulations of fires, CFD and FDS in order to have a good background for the validation.

8.1 The history of fire simulation

The use of computer-based fire simulation has gone hand in hand with the performance of computers and their development (Rubini 2008). The zone models (two-zone models) were the first approach to be widely accepted and used, much because of its simplifications which results in relatively low computer power demand. The two-zone model splits the enclosure into two zones, one hot upper layer and one cold lower layer. With today's computer power the zone models performs a simulation in a matter of seconds.

The more complex approach to simulate fire is by the use of CFD. Amongst CFD there are also a number of different approaches to simulate the reality, see section 8.2. CFD models demand much more computer power then two zone models and have therefore had a limited use in engineering applications upon until a few years ago (for smoke spread). Earlier, CFD was first of all a tool in research projects. If one should make a difference between the different CFD-codes then the RANS-code, see section 8.2, has been used more in the past because it, under some circumstances, is more computationally efficient then the other common CFD-code LES, see section 8.2. Today the tendency is that the LES-code is taking over more and more (Rubini 2008), because computer power now allows for transient fire behaviour.

8.2 What is CFD?

CFD is short for Computational Fluid Dynamics and it is a way to numerically solve the governing equations of fluid dynamics. The equations solved are first of all the set of Navier stokes equations, continuity and conservations equations for energy, mass, velocity and species. The reason why the equations are solved numerically is because no one has yet presented an analytical solution for the full Navier Stokes equation (Rubini 2008b).

In the programs a calculation domain is specified and portioned into small cells called grids. It is in these grids that the conservation equations are solved. There are different kinds of approaches for solving the equations.

DNS

DNS stands for Direct Numerical Solution and is, as its name implies, a direct way to numerically solve the transport equations. This requires a resolution at Kolmogorovs micro scale. This is the smallest scale where turbulence is the governing parameter which equals to about 10^{-6} m in the length scale (Rubini 2008c). This makes it impracticable for engineering problems because of the computer power that it demands.

In FDS, see below, it is possible to perform DNS calculations if the grid is set fine enough

LES

LES stands for Large Eddie Simulation and it assumes that all the turbulent energy is preserved in the largest scale, i.e. everything under the largest scale (grid) is not calculated. If the grid is set fine enough LES converts to a DNS. To deal with phenomena that take place under the grid scale, the code use so called sub grid models like combustion or radiation models. The code works on a transient time line and the time step is therefore limited since every calculation is based on the calculation the time step before (Rubini 2008d).

FDS is a fire simulation computer program based on a LES-code. FDS stands for Fire Dynamics Simulation and is first of all a model for transient fire driven flow. The program is developed by the National Institute of Standards and Technology (U.S. Department of Commerce). FDS is a dos-program and any visualisation is done in an additional program, in most cases the program Smokeview. FDS has been working for over 35 years but it became public in the year of 2000 (McGrattan et al. 2008b). Since then, further upgrade has continued and today's version is the fifth large release. The program is free of charge and can be downloaded from the internet.

RANS

RANS stands for Reynolds Averaged Navier Stokes (equations) and its approach is to decompose instantaneous values to a mean value with fluctuations. A RANS-code is most often used for steady state simulations because it executes Taylor expansion series with convergence for every time step (Rubini 2008d). This makes it independent of what has happened earlier (in time) in the simulation which is appropriate for steady state fires. If it is desirable to do a transient simulation with many time steps then the program is not so time efficient.

SOFIE is a fire simulation computer program based on a RANS-code. SOFIE stands for Simulation Of Fires In Enclosures but is despite its name written to handle other fluid dynamics problems then just fire dynamics (Rubini 2006). The program is developed by several institutes, e.g. Cranfield University and SP Technical Research Institute of Sweden and the University of Lund. SOFIE is a dos-based program and requires a pre-processor for the geometry of the enclosure, for example the program AC3D. A program for visualisation of the results is also necessary and the program MAYA VI can be used. SOFIE is free of charge and can be downloaded from the internet.

Application

CFD is used in different areas but for smoke filling of enclosures the application is mostly that of research or analytical fire safety design in buildings. Fire safety design consultants are the ones who most frequently use CFD for smoke filling of enclosures (in Sweden). It is most often used for verification of analytical solutions for buildings fire safety design. A typical analytical dimensioning that includes CFD and FDS is an evacuation investigation. In such a dimensioning there are critical parameters that need to be investigated. The parameters like the height of the smoke layer, the temperature, the visibility and the toxicity are often used. These parameters can be addressed by using FDS which calculates them on a transient time line. The time to critical conditions are then compared to the evacuation time.

8.3 FDS and the Mixture Fraction combustion model

As mentioned previously, FDS uses sub-grid models to calculate that which cannot be resolved in the largest eddy (grid). An example of this is the combustion model which by default assumes a single step reaction with predestined products that happen infinitely fast. The combustion model used by FDS is a “mixture fraction model” or “mixed is burnt model”. As its name implies it is mixing controlled which means that when fuel gases and oxygen mix they are immediately and completely burned. This is a good approximation for well-ventilated fires but not so good for under-ventilated fires. For under-ventilated fires the heat release rate would be too high and burning would take place where it should not. To account for this, FDS uses a simple empirical expression that describes the condition whether or not the mix of fuel vapour and oxygen are allowed to burn.

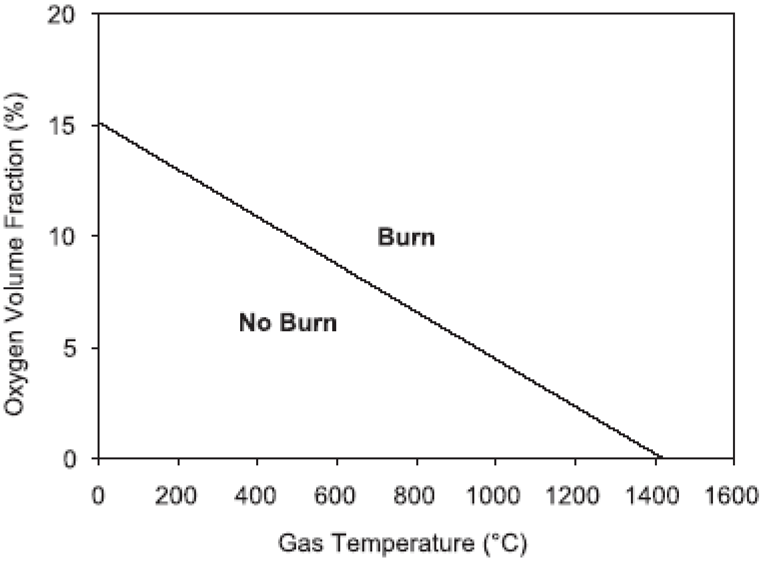


Diagram 8.1: The correlation for when the fire is allowed to burn (McGrattan et al. 2008).

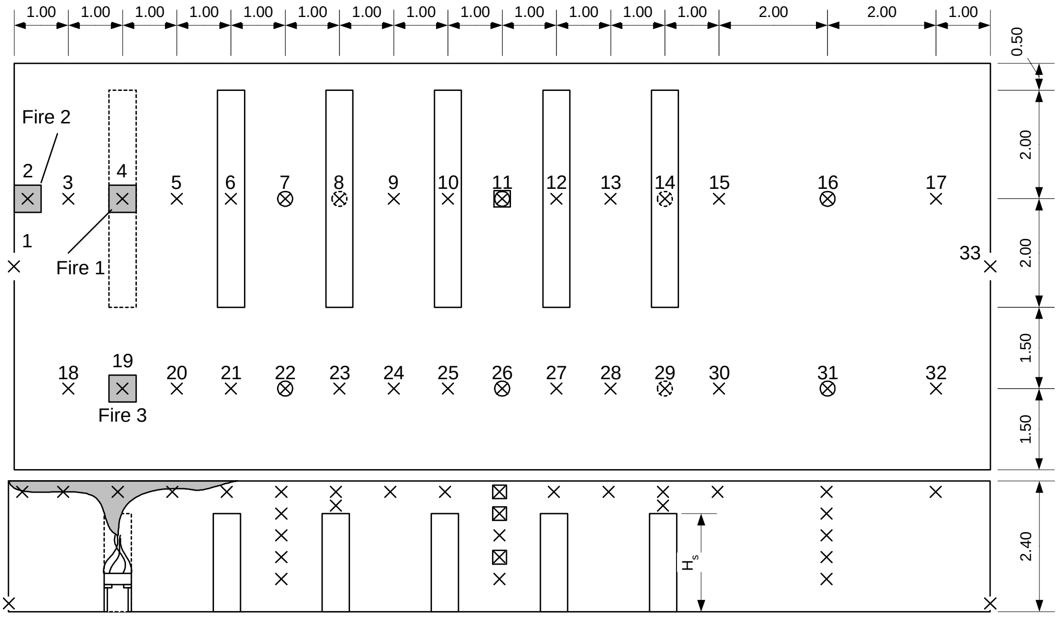
This simple expression is however linked with several problems. The most important error is its grid dependence. The temperature of the flame is very dependent on the grid resolution. A fire may burn in one resolution but not in another. Because the temperature in the flame increases with a finer mesh resolution the fire may go out in the simulation while it would burn in the reality. A second important error is that of adiabatic flame temperatures that FDS assumes. In reality the temperature is not adiabatic but instead lower which can lead to that the fire in the simulation goes out after the real fire (Holmstedt 2008).

In FDS 5 there is a new feature, the single step reaction can be replaced with a two step reaction where the formation of carbon monoxide and its oxidation can be tracked and calculated.

8.4 Experimental data

8.4.1 Experimental set-up

The fire tests were performed inside a rectangular (3 dimensions) room build in the SP fire hall. The purpose was to simulate a retail premises with both areas with shelves and open areas without shelves. The lay-out of the room is shown in Figure 8.22. The dimensions of the room was 18 m × 7.5 m × 2.4 m and were chosen to represent 1:2 scale of retail premises with the dimensions 36 m × 15 m × 4.8 m.



× = Thermocouple
⊗ = Thermocouple tree (9 TCs)
⊗ = Smaller thermocouple tree (3 TCs)
☐ = Laser/photo cell

Figure 8.2: Experimental set-up and measurement positions (Lönnermark & Björklund 2008).

Three different pool sizes were used: 1) 305 mm × 305 mm × 100 mm, 2) 500 mm × 500mm × 150 mm, and 3) 650 mm × 650 mm × 150 mm. The amount of fuel (a depth of approximately 60 mm) was chosen to give a burning time of approximately 15 minutes. Heptane was used as fuel. A water layer was added to give a free board of 10 mm in all three cases, i.e. 30 mm of water for pool 1 and 80 mm of water for pool 2 and pool 3.

Most of the tests were performed with the fire in the position “Fire 1”. For comparison a few tests were performed with two other fire positions (see figure 8.2 and table 8.1).

Simulated shelves were included in six of the tests. The shelves were made as blocks 4 m long and 20 cm wide. The height of the shelves, H_s, was 1.8 m. The material in the blocks was wooden joists covered with incombustible boards. The reason for the design of the simulated shelves was to study the effect the shelves in the over all smoke spread and not to study fire or smoke spread within the shelves. The fire position Fire 1 was at the centre of an imagined shelf if the same distances were to be used between all the shelves. There was, however, no shelf placed in this position. This is marked as a dashed line in figure 8.2. Fire position “Fire 1” simulates a fire in a free standing shelf, while position “Fire 2” simulates a fire in a pallet load or display and position “Fire 3” simulates a fire in a shelf fixed to the wall.

8.4.2 Measurements

Different parameters were measured and these were:

Smoke density

The optical density i.e. the smoke density was measured by using laser/photocell-system. The lasers were transverse lasers with an optical power of 5 mW and a wavelength of 650 nm. Both lasers and photocells were placed inside boxes with overpressure. Each box had a tube for the light in the measuring direction. The measuring distance (distance between the ends of the tubes) was 0.5 m. The equation used to describe the smoke density or optical density was:

$D_L=-1/L \ln(I/I_0)$

Where L is the distance between the transmitter and the receiver.

Temperature:

The temperature was measured using thermocouples placed out as shown in figure 8.2. Two different types were used, 0.8 mm and 0.25 mm. In the diagrams below their height is related to the distance from the ceiling.

Velocity:

The velocity was measured through the two small openings of the room by bidirectional probes (McCaffrey & Heskestad 1976) and calculated using the differential pressure equation.

Mass loss rate:

The mass loss rate was measured by placing the fuel container on a scale and measuring about every second. The mass loss rate presented in the diagrams has been "smoothed" where every time step is the mean value of 11 measurements, five seconds before and five after. This is done to simplify the presentation of the overall change in the mass loss rate.

It is hard to say anything direct about the heat release rates in the different cases since there is no exact knowledge about the combustion efficiency.

Oxygen

The oxygen level was measured by sucking out the air to a receiver with an oxygen analyzer (PMA 10).

The tests were monitored by the staff at SP. The cases were also recorded by different video cameras from different angles, information about these recordings can be found in *"Smoke spread and gas temperatures during fires in retail premises –Experiments and CFD simulations*" (Lönnermark & Björklund 2009).

8.4.3 Experimental procedure

The tests started with two minutes of background measurement before ignition (this time is not included in the output of the results). This was done to get a steady background exposure. The ignition of the pool fires were done manually with matches which led to that the door was opened for about 30 seconds. When ignited, the pool was let to burn until all fuel was consumed. Three different parameters were changed between the tests: the size of the fire, the position of the fire, and with or without shelves. The test program is presented in table 8.1.

Table 8.1: Test program.

Test no	Fire size [mm × mm]	Fire position	Shelves	Amount of fuel [L]
1	305 × 305	Fire 1	Yes	5.42
2	500 × 500	Fire 1	Yes	15.0
3	500 × 500	Fire 1 *)	Yes	15.0
4	650 × 650	Fire 1	Yes	15.0
5	500 × 500	Fire 2	Yes	15.0
6	500 × 500	Fire 3	Yes	15.0
7	305 × 305	Fire 1	No	5.42
8	500 × 500	Fire 1	No	15.0
9	500 × 500	Fire 1 *)	No	15.0
10	650 × 650	Fire 1	No	15.0
11	500 × 500	Fire 3	No	15.0

*) Repetition test

8.4.4 Results

In this section the results for the eleven tests are presented, it is mainly the mass loss rate, the temperature and the oxygen level that is presented. In *"Smoke spread and gas temperatures during fires in retail premises –Experiments and CFD simulations*" (Lönnermark & Björklund 2009) the total amount of output data is presented.

The tests all have different results but test 1-4 and test 7-10 have the same configuration with the exception that there are shelves test 1-4 and not in test 7-10.

Test 1 and 7

For test 1 and 7 the maximum mass loss rate is approximately 3-5 g/s which with a complete burning would correspond to about 130-220 kW (ΔH_c=44.6 MJ/kg). The mass loss rate stays at its maximum for about 20 minutes after which it quickly goes down for a burn time of 25 – 30 minutes, see diagram 8.2. The mass loss rates in the diagrams below are averaged with 20 seconds for test 1 and 10 seconds for test 2-11. This is done to be able to present the overall change in mass loss rates but there is still fluctuations like in the diagram below which is a result of the scale is very sensitive and that measurements are taken so frequently.

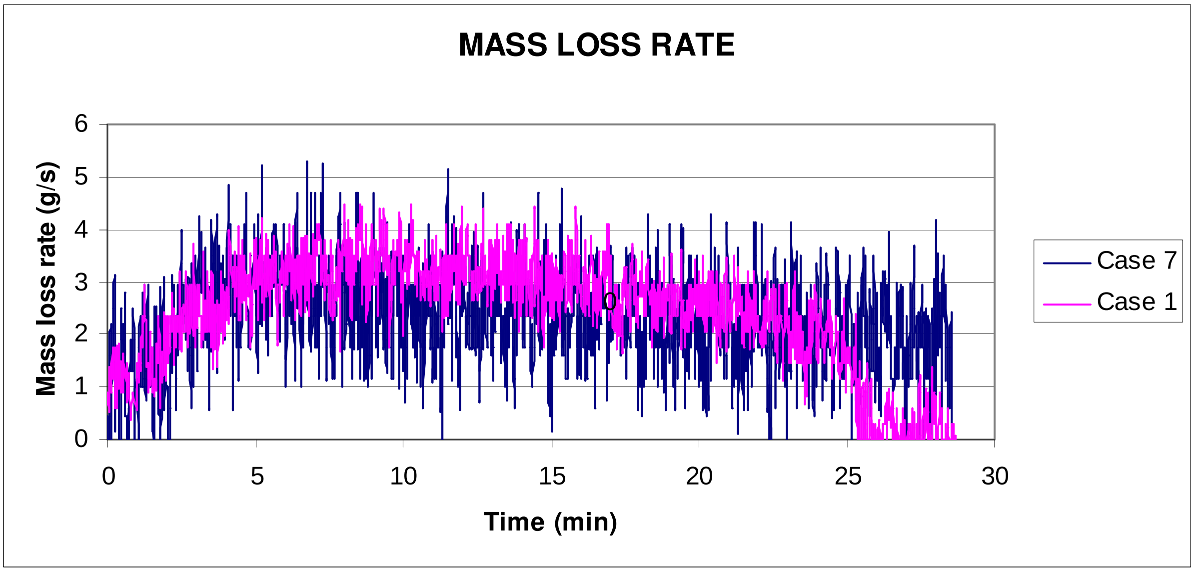


Diagram 8.2: Mass loss rate for test 1 and test 7.

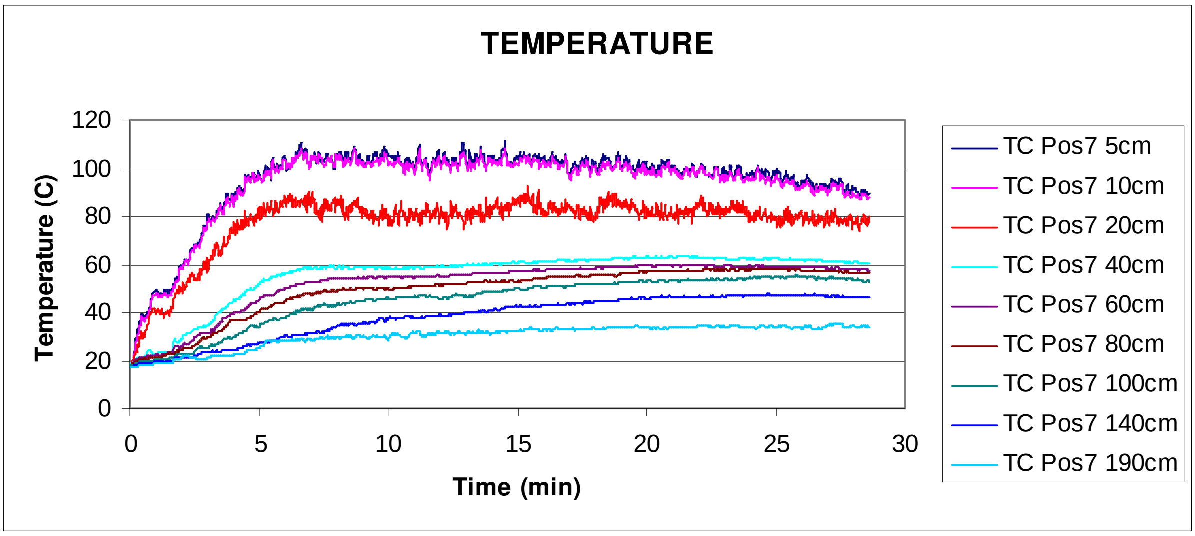


Diagram 8.3: Test 7 with the fuel area 305 × 305 mm.

Test 2-3 and 8-9

Test 2-3 and 8-9 had a maximum mass loss rate of about 13 g/s which with a complete burn would correspond to 580 kW. The mass loss rate stays at its maximum for about 5 minutes after which it gradually decreases for a complete burn time of 17-19 minutes, see diagram 8.4.

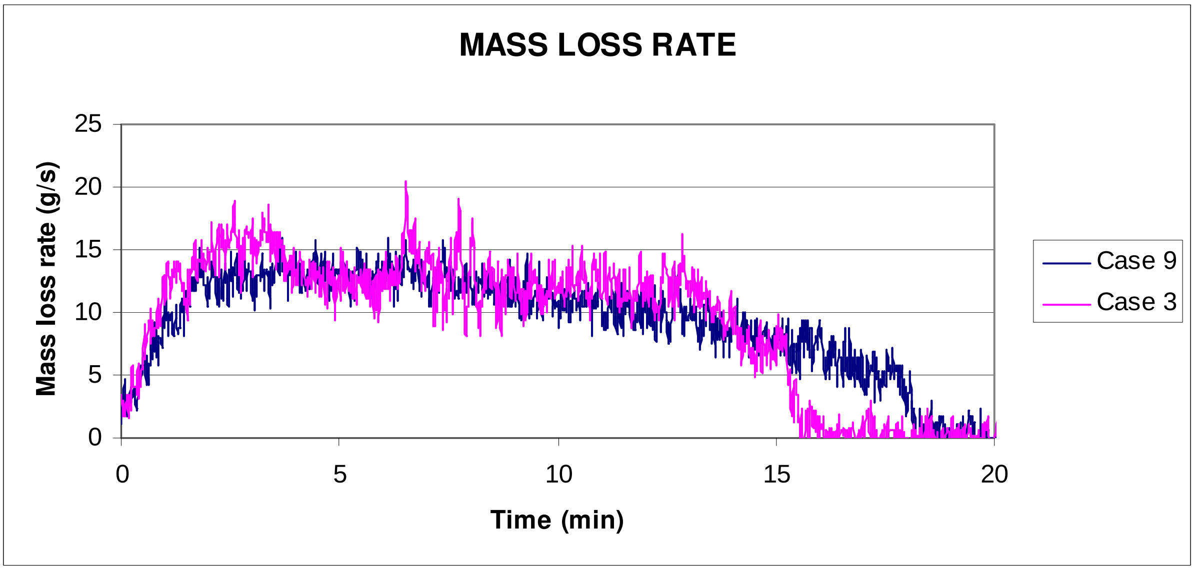


Diagram 8.4: Mass loss rates test 3 and test 9.

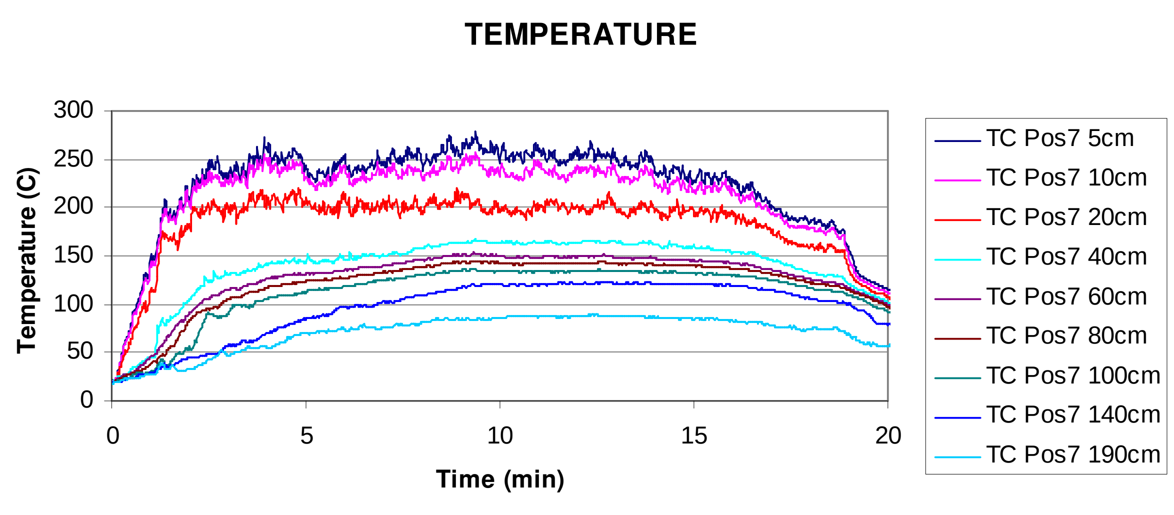


Diagram 8.5: Test 8 with the fuel area 500 × 500 mm.

Test 4 and 10

Test 4 and 10 had a maximum mass loss rate of 30-35 g/s which with a complete burn would correspond to 1340- 1560 kW. The mass loss rate stays at its maximum for no more then two minutes after which it goes down in stages giving it a burn time of 8-9 minutes, see diagram 8.6.

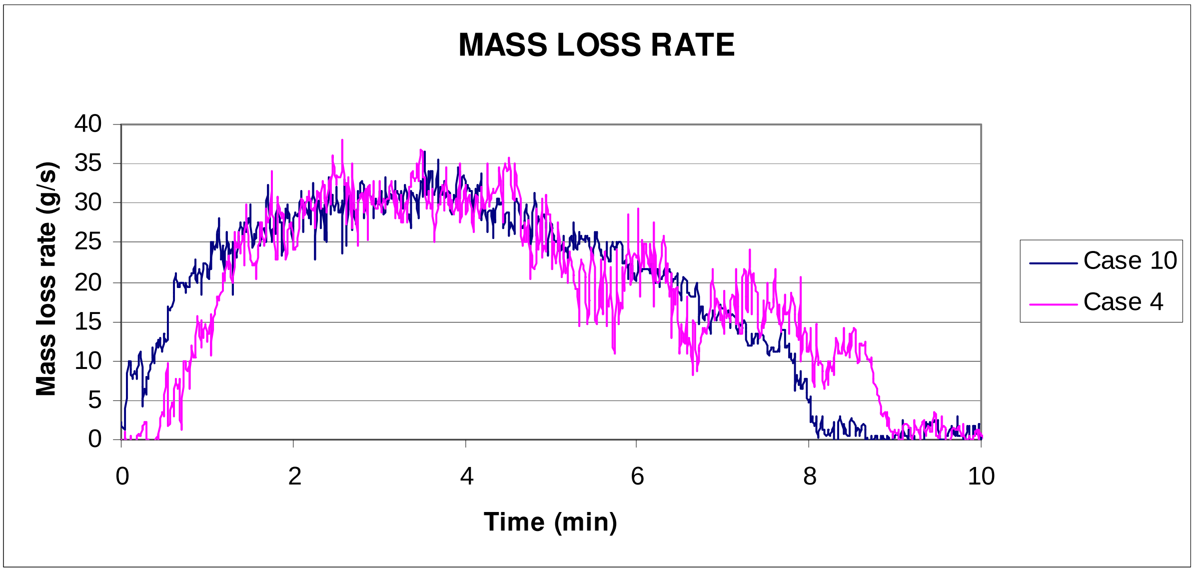


Diagram 8.6: Mass loss rates test 4 and test 10.

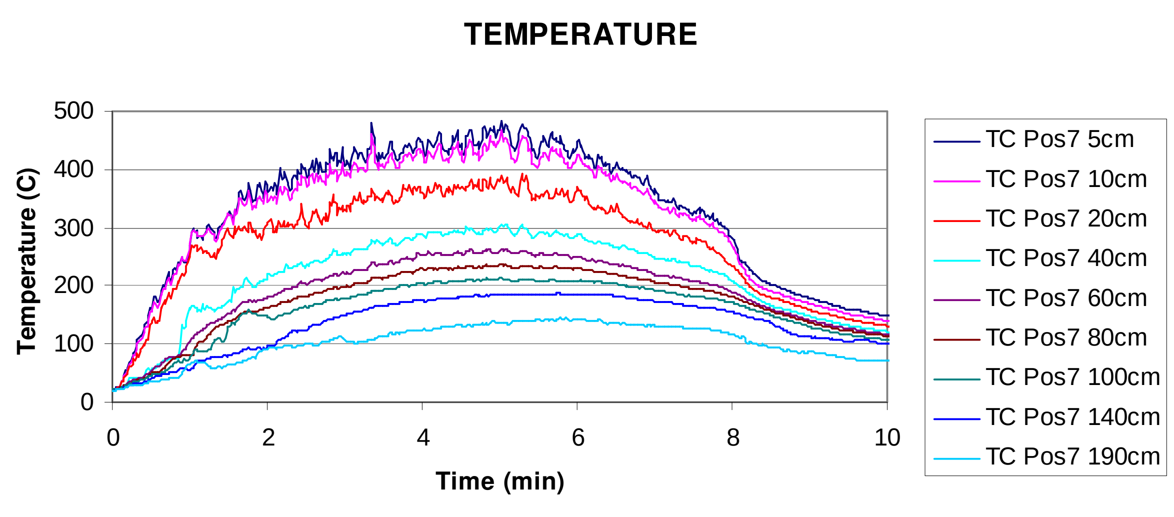


Diagram 8.7: Test 10 with the fuel area 650 × 650 mm.

Test 5, 6 and 11

In test 5 and 6 the fires had other placements then in the rest of the tests. In test 5 the fire was placed flush to the wall which resulted in a higher maximum mass loss rate then the other fire with area of 500 × 500 mm, compare diagram 8.3 and diagram 8.5. In test 6 the fire was placed out on the floor and its mass loss rate followed the fires with the same fire area, test 11 was a repetition test of test 6 but without shelves.

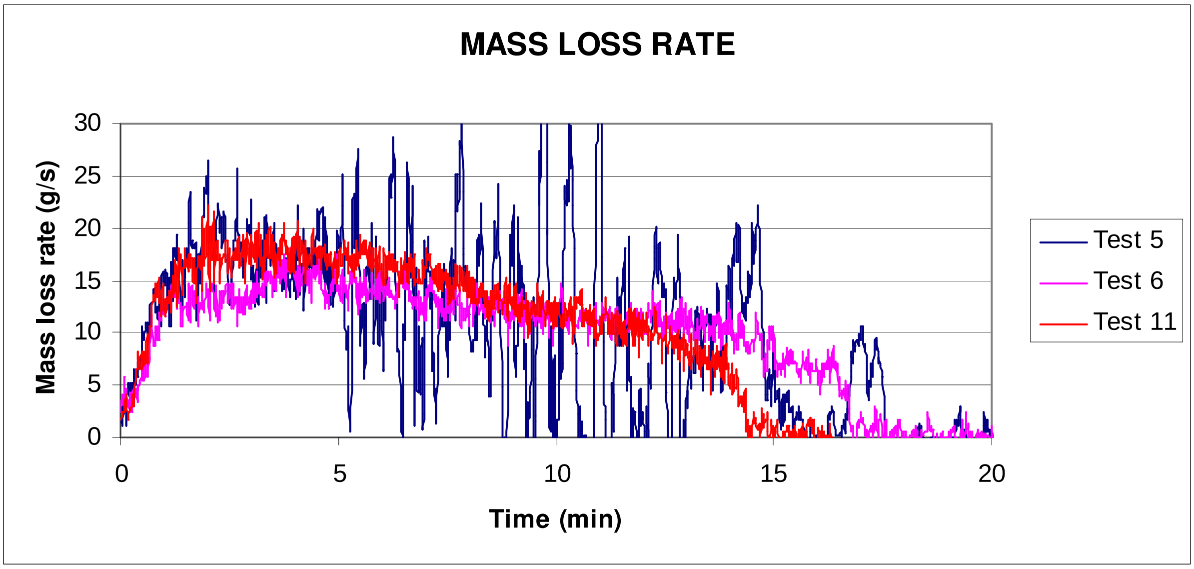


Diagram 8.8: Mass loss rate test 5, 6 and 11.

The mass loss rates and the temperatures in test 1 and 7 show no direct signs of being under-ventilated see diagram 8.2 and diagram 8.3. The curves for the mass loss rate and the temperatures in test 4 and 10 shows signs of being under-ventilated see diagram 8.6 and diagram 8.7. In the two large fires the mass loss rate, after reaching its peak, slowly start to decrease where a well-ventilated fire have an approximately constant mass loss rate and a quick decrease when the fuel runs out.

The oxygen level in test 10 reach as low as about 9 vol % (80 cm down from the ceiling), see diagram 8.9, which indicate that the fire is ventilation controlled. In test 7 however the oxygen level stays above 19 vol %, see diagram 8.9, and should not be ventilation controlled.

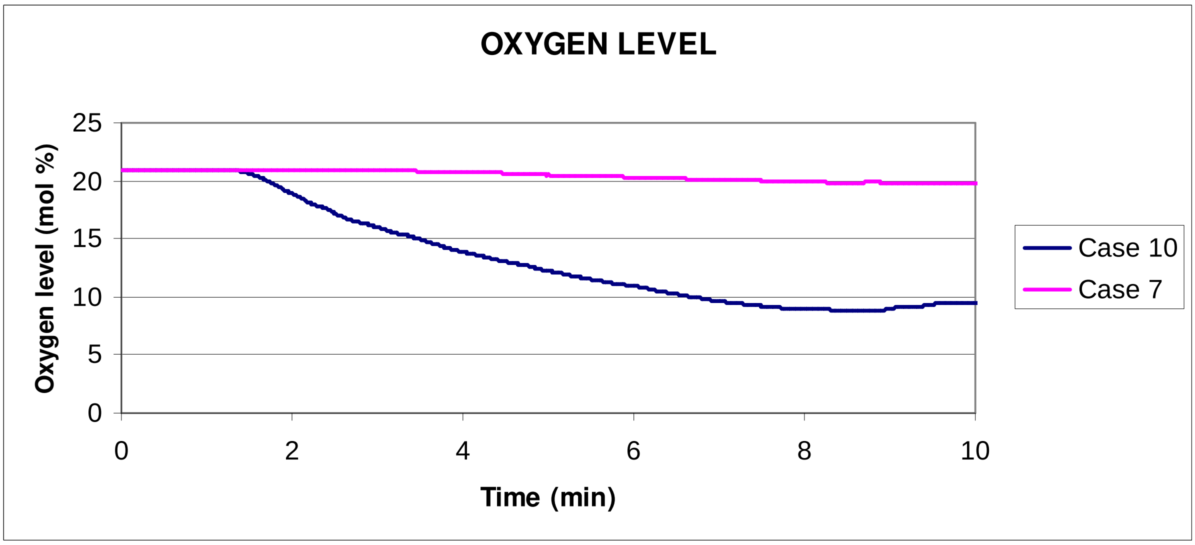


Diagram 8.9: Oxygen level for test 7 and 10.

Results for the smoke fill are presented in table 8.2. Test 1 and 7 had difficulties of building up a distinct hot upper gas layer and the conditions were close to well mixed.

The results displayed in table 8.2 are based on visual observation of a video capture. It is always difficult to see the exact where the smoke layer begin and the result presented in table 8.2 should not be seen as exact results but merely as approximations.

Table 8.2: Smoke fill results, time in minutes.

Hight above floor	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11
1.8	15*	2	2	1	2.5	3.3	21.5*	2	2.5	1	2.5
1.5	19*	2.5	2.5		3	3.5-4	26.5*	2.5	3	1.5	3.5
1	19*	6	5	2.5	4	5.5	30*	5	5	2.5	4.5
0.5	24*	6.5	6	3	4.5				7.5	3.5	5.5
Completly dark		7	7.5	3	5	7.5		7	8	3.5	6

** well mixed scenario*

The results for the smoke density show that the difference in smoke density for the well-ventilated fire and the under-ventilated fire (Test 7 and 10) is approximately a factor 5, compare diagram 8.10 and diagram 8.11.

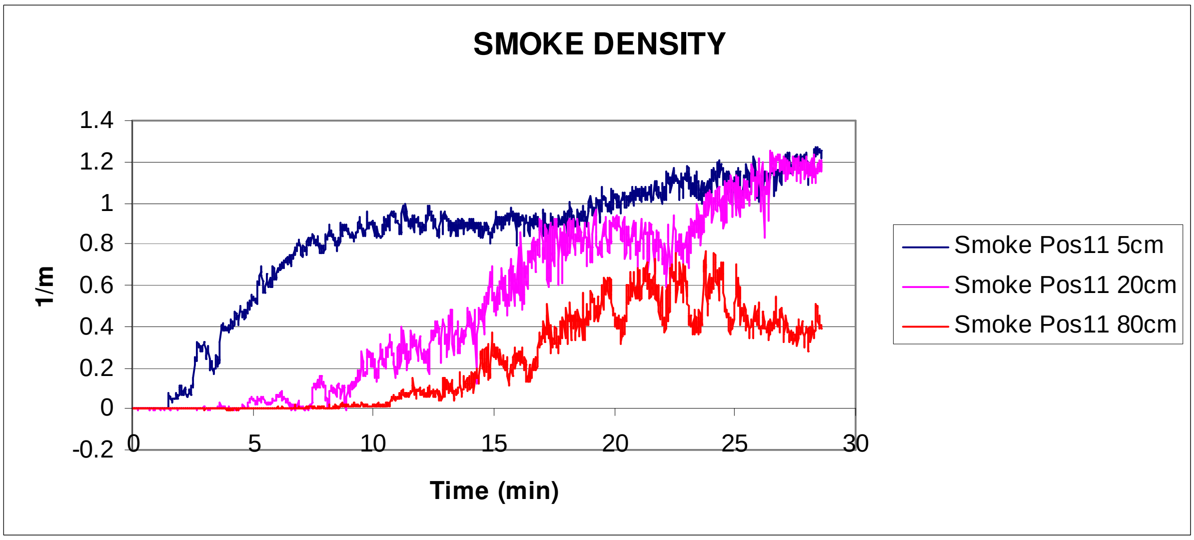


Diagram 8.10: Smoke density for test 7.

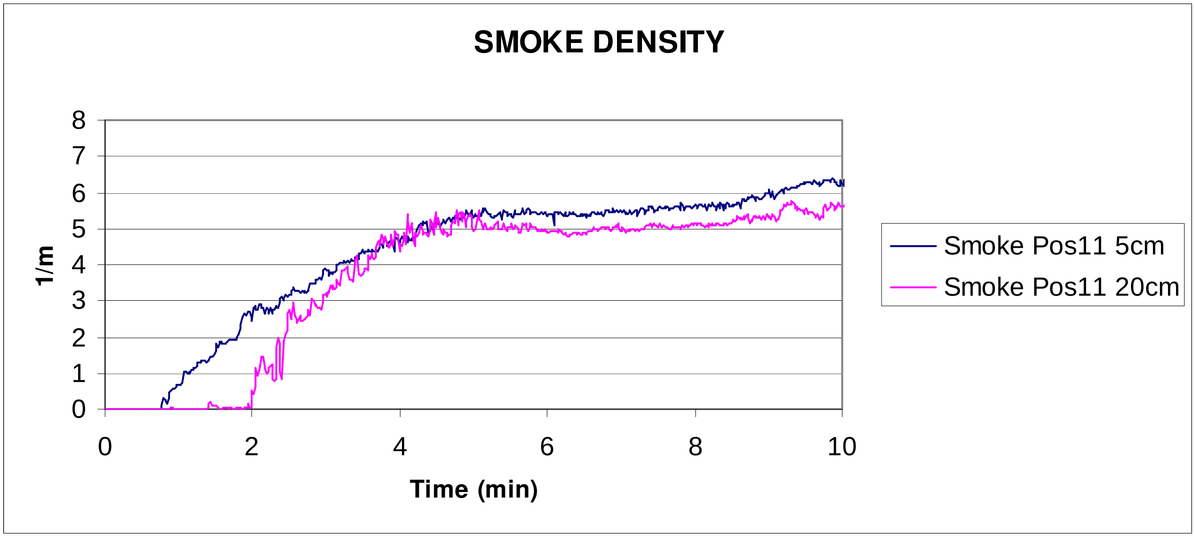


Diagram 8.11: Smoke density for test 10.

8.4.5 Sensitivity and error factors

As discussed in section 4.3 it is important to realize that the presented results are not the actual conditions in the reality but merely a measure of the reality. Differences exist because the measurement equipment contains error and uncertainty factors. To validate FDS for under-ventilated fires this uncertainty must be quantified. For the experimental results this can be done by comparing different measurements. For the temperature this can be observed by looking at the thermocouples. There were thermocouples with a diameter of 0.25 mm and thermocouples with a diameter of 0.8 mm. The thickness can create different readings since the “thinner” takes up and gives away energy faster then the “thicker” (thermal inertia). The difference is small and does really only exist during the build up and the decline phase which probably is a result of the thermal inertia, when the temperature stabilizes in the room then there is almost no difference. The largest difference in real numbers is closest to the ceiling but is in percentage about the same, around 10 %.

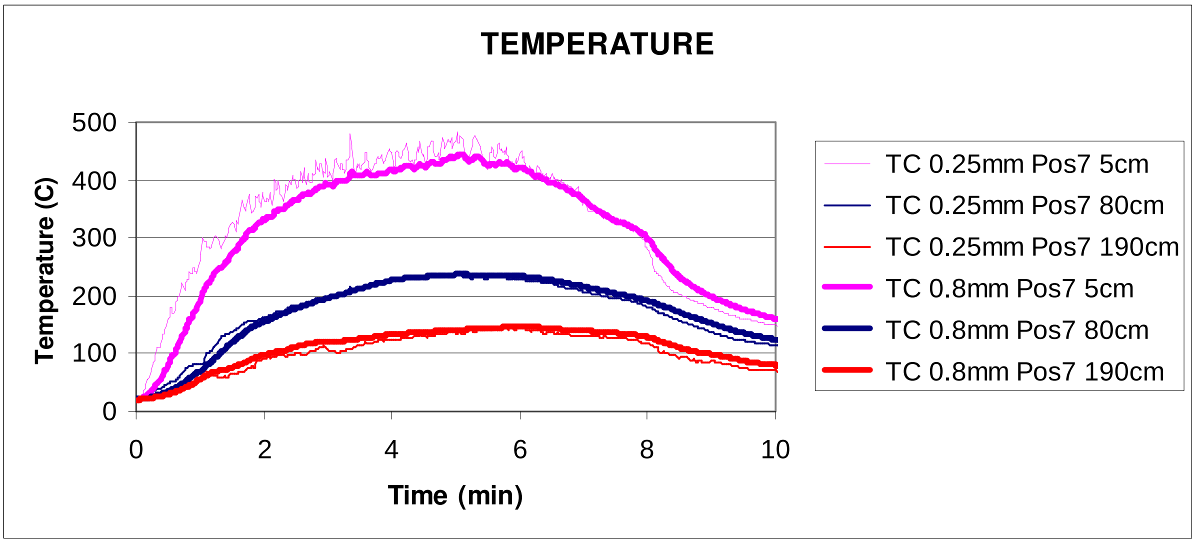


Diagram 8.12: Comparison between 0.25 mm and 0.8 mm thermocouple (test 10).

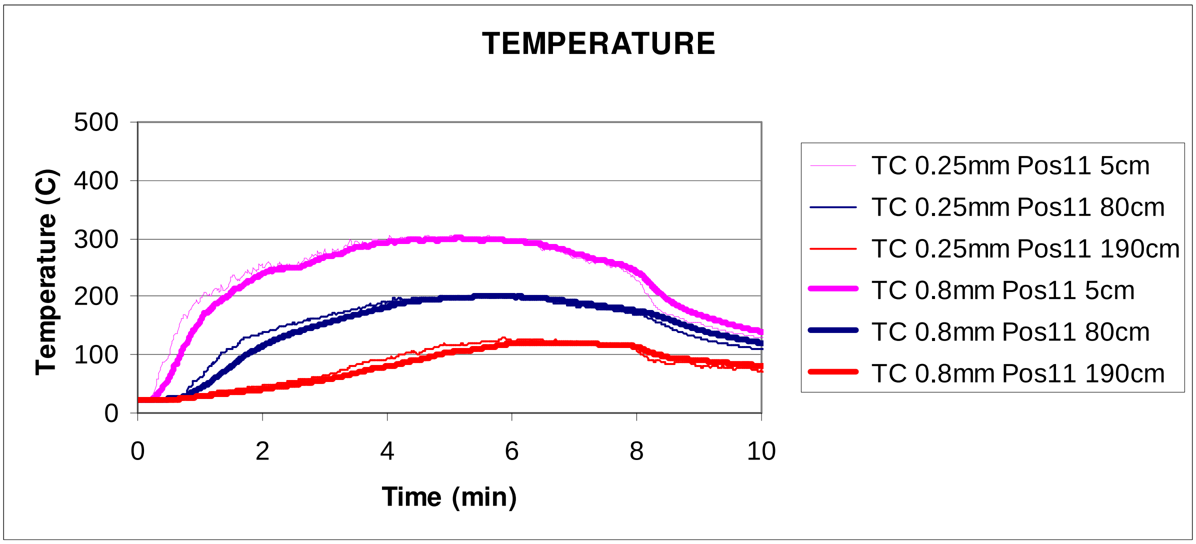


Diagram 8.13: Comparison between 0.25 mm and 0.8 mm thermocouple (test 10)

The scale is another source of uncertainty and can have a big impact on the results. By comparing the mass loss rate between two tests with the same configuration the uncertainty of the scale can be estimated. There are of course many other factors that can affect the results, like for example the initial temperatures of the walls and the temperature of the fuel container. Despite this the resemblance between test 8 and 9, see diagram 8.14, is almost non-existent.

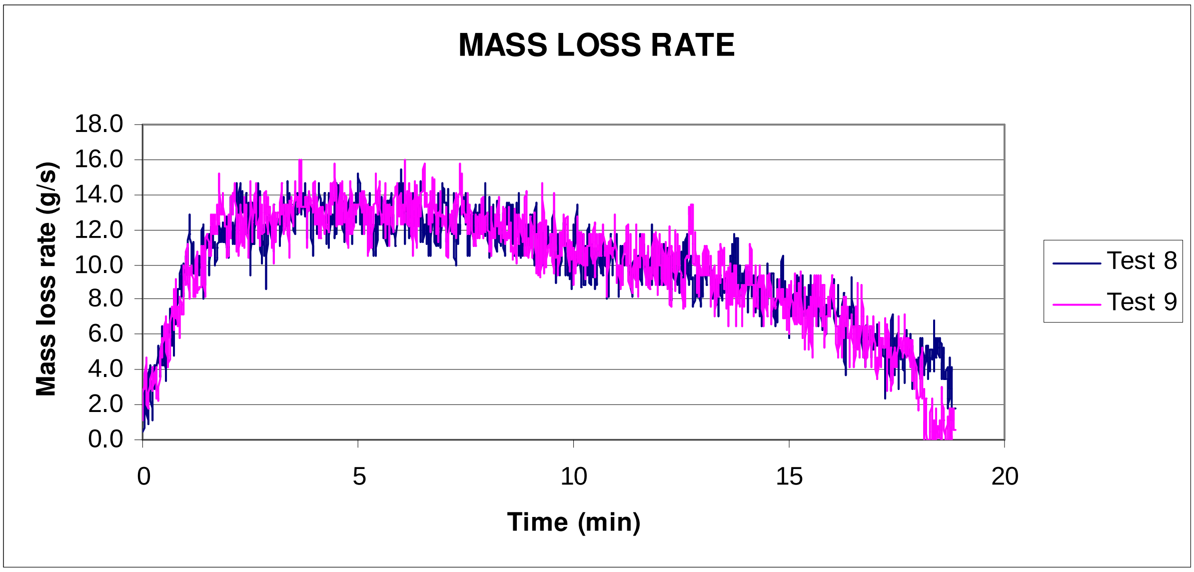


Diagram 8.14: Comparison between mass loss rates in test 8 and test 9.

The visibility is measured via a "beam detector" which measures the light extinction over a certain length. In the tests the equipment were placed in over pressurized boxes which decreases the possibility of that the transmitter and the receiver gets dirty. In diagram 8.15 the resemblance between the smoke densities can be viewed, the difference is the biggest closest to the ceiling but for the other measuring points the difference is less then 10 %.

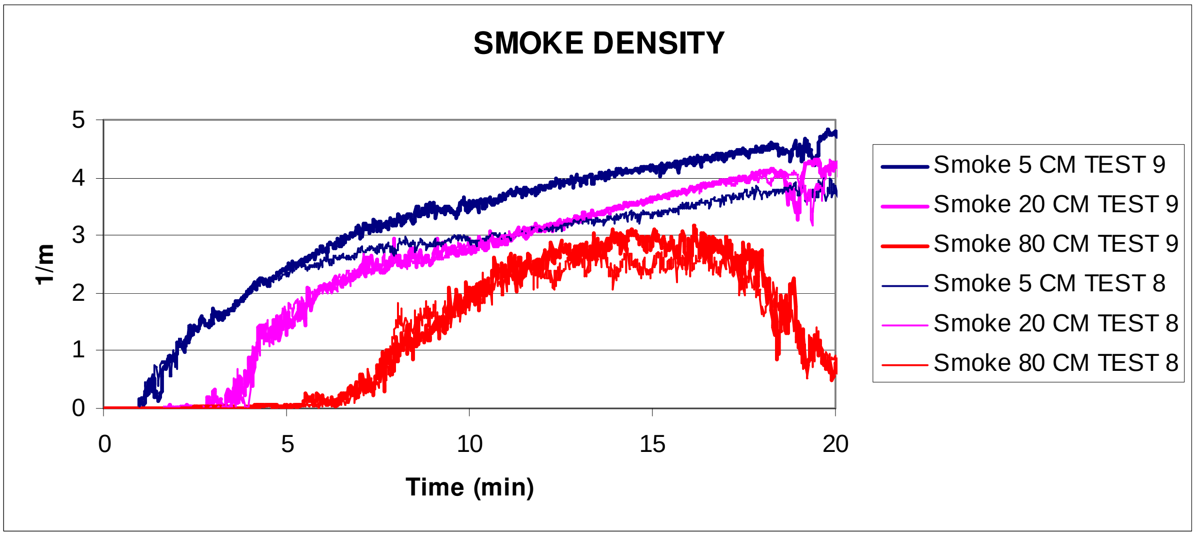


Diagram 8.15: Comparison of the smoke density in test 8 and 9 (pos 11).

The placement of the velocity measurements, which are done via bidirectional probes, are very important. If they are placed "in the opening" or just inside or outside can make a big difference. In the experiments they were place in line with the outer wall. The vertical placement is even more sensitive since there can be a very high velocities in the top of the hole and quite low in the middle. The velocity results are therefore hard to use in a good way and can really only be used to say in which direction the flow goes.

How long time it takes before the doors it shut behind "the igniter" is important for the pressure build up in the room, for the last 6 tests (test 5-11) the data shows that the igniter usually shut the door after 30 – 40 seconds, which is a relatively small timeframe and therefore with a relatively small pressure build up difference.

Another factor that affects the results is the leakage area, the size and the position of it. If there is a little amount of leakage area then the pressure is likely to build up. If the leakage area is situated in the top of the compartment then the hot gases leak out. If the leakage area is situated in the bottom of the compartment then air i.e. oxygen can leak out. The extent of this is hard to describe and have only been estimated to be small by the supervisor of the test (Lönnermark 2008b).

The comparison in this section is not the exact difference between the reality and the tests but only an estimation of a difference caused by the measuring devices. The actual difference between the reality and the measurements may be more or less but is at least combined with an uncertainty factor of the magnitude described above.

8.4.6 Discussion

The sizes of the fires are important for the mass loss rate and the heat release rate. One big difference between the tests is that for the small fires (for example test 1 and 7) there are no signs of a ventilation controlled fire. The mass loss rate stays approximately constant, see diagram 8.2. For the two larger fires (test 4 and 10) there are phenomena that indicate ventilation controlled fires like pulsations of smoke outside the openings (Lönnermark & Björklund 2009). The mass loss rate for these tests also indicates a ventilation controlled fire since the mass loss rate first goes up fast and then decreases over time long before it goes out. If the fires would have been fuel controlled then they should have stayed constant and then quickly go down when the fuel begins to run out. This makes sense since the fires could be expected to be fuel controlled in the beginning and as the oxygen is consumed the burning efficiency goes down. The oxygen level in test 10 reach as low as about 9 vol %, see diagram 8.9, 80 cm down from the ceiling, which indicate that the fire is ventilation controlled. In test 7, however, the oxygen level stays above 19 vol %, see diagram 8.9, and is not be ventilation controlled.

The uncertainty and error factors in the experimental results i.e. the different measuring devices have been estimated by comparing different test and different measuring devices. The differences between the temperatures, the smoke density and the mass loss rate are all around 10 % or less. When dealing with a turbulent phenomenon like a fire, 10 % is a quite small uncertainty factor. The uncertainty that exist through the 10 % will be brought up in the discussion of how big the difference is between the results generated by FDS and the results in the experiments, see section 8.5.4.

8.4.7 Conclusion

Depending on the sizes of the fires they are more or less ventilation controlled. The tests with small fires (test 1 and 7) show no direct signs of being under ventilated and test 1 and 7 can be said to be fuel controlled. The larger fires show more signs of being ventilation controlled, where pilot flames and smoke pulsation occurred at the openings. Test 4 and 10 can therefore be said to be ventilation controlled. Test 7 and 10 will be used in the simulations because test 7 is fuel controlled and test 10 is ventilation controlled. Test 5 and 6 will not be simulated since there only were one of each experiment performed, which gives little possibility for comparison. The reason why test 7 and 10 is used instead of test 1 and 4 is because there are no shelves in test 7 and 10 which limits possible effects that may make the CFD validation more difficult.

The uncertainty factor in the experimental results related to mass loss rate, temperature and smoke density is of a magnitude of 10 % or less. The difference for the temperature is at its maximum during the build up end the decline phase, in between these phases the difference is very small and has a better match with other similar work e.g. *"Uncertainties in measuring heat and smoke release rates in the room/corner test and the SBI"* (Axelsson et al. 2001).

8.5 Simulations

The simulations are done to validate the FDS-code for under-ventilated fires. The SP tests that were chosen for comparison are nr 7 and number 10, see chapter above.

The simulations are done with FDS Parallel version 5.1.6 (windows 64 bit) and are performed on a computer cluster at the University Collage of Borås. The cluster consists of 8 dual core processors and approximately 64 Giga byte of RAM-memory.

8.5.1 The process

Initially the properties of the materials in the scenario were investigated and the properties of the heptane were chosen after discussion with Göran Holmstedt (Holmstedt 2008). The soot yield and carbon monoxide yield were chosen for well ventilated fires. The meaning of the chosen yields for soot and carbon monoxide should not be taken too serious. The reason for this is that the fire will reach ventilation controlled stages for case 11, where the well ventilated yields will not be accurate. The properties of the construction materials were taken from *Smoke spread and gas temperatures during fires in retail premises – Experiments and CFD simulations*" (Lönnermark & Björklund 2009). The geometrical setup was done so that the enclosure was surrounded by air.

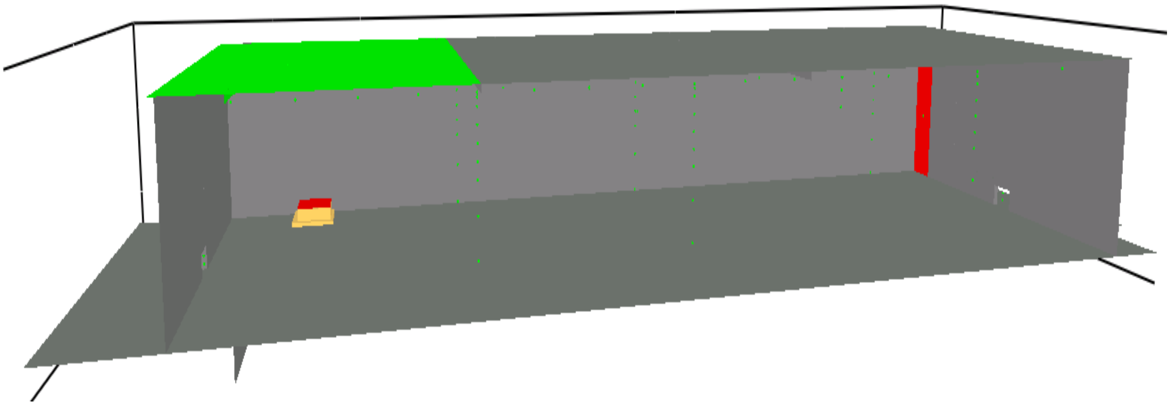


Figure 8.3: Geometrical setup, the green is ceiling section with insulation, the red in the short wall is the door.

Since the calculations were done in parallel system of 8 cores, the computational domain was divided into 8 meshes and each mesh was then calculated on a separate core. The setup was done after the experimental set up and can be viewed in figure 8.4. A finer mesh was used around the fire and the total amount of grids, in the base scenario, were about 600 000, for number of grids per mesh see appendix Y.

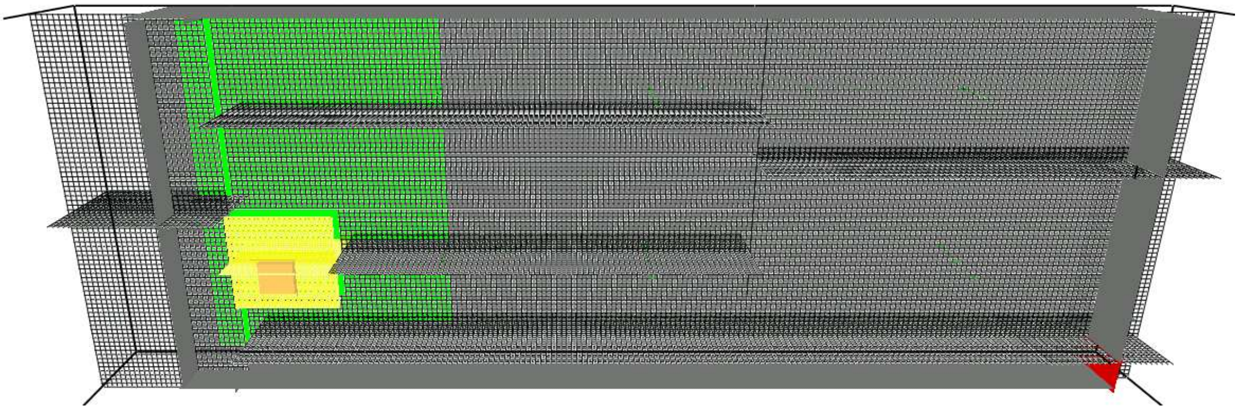


Figure 8.4: The mesh setup seen from below, each vertical mesh line indicates a mesh, the yellow is the fire mesh.

Initially much time were spent on trying to get FDS to work as optimal as possible. According to the FDS user guide (McGrattan et al, 2008) and other work by Dittmer and Jämtäng (2006) there is not much time to gain with the use of unsynchronized meshes in a parallel simulation. The reason for this is because when the mesh with the smallest time step is taking up most of the computer time, the other meshes with a longer time step just sits and wait to be updated. But if the meshes with the smaller time steps contain lesser number of grids than the coarser, then the fine and the coarser mesh could be designed to have same computer work load.

The fire growth were controlled via the mass loss rate which was set after the experimental results, see FDS input file in appendix W.

Assumptions and Simplifications

Geometrical simplifications were done for the small openings where the 5 cm plinth at the floor was ignored (because of the mesh resolution). In the experiments the ceiling furthest away from the fire (3.4 m from the door wall) were made of 6 mm Masterboard instead of 10 mm Promatect, this was ignored and Promatect was used. Furthermore, the legs of the fuel table were ignored.

One important simplification is that of no leakage areas. This is the case since leakage almost always is in form of small cracks which are smaller then the finest grid cell size. In FDS there is a function to simulate leakage area but that can only be applied for enclosures with no openings and can therefore not be used in this case. To simply open a slit that would match the leakage area is not a good approach since that would have large affect on the flow fields. It is hard do estimate the leakage area but according to the supervisor it was small (Lönnermark 2008b).

Models used

By default FDS has several models for describing for example sub-grid phenomena, see FDS User (McGrattan et al 2008b) and Technical guide for complete list (McGrattan et al 2008). Models which have been included by active choice is the “grey gas radiation model” with 104 solid angles and 15 polar angles. Heat transfer through walls were also chosen since the hot gases thermal interactions with the walls were of importance.

8.5.2 Results and Comparison with SP tests

In the simulations the fires are defined as a ventilation opening that releases heptane. It is the mass loss rate that is specified in the FDS input script, see appendix W. The heat release rates is then decided by the conditions in the enclosure, in the diagrams below the heat release rate in the simulations are referred to as *predefined* heat release rate.

Case 7

In case 7 the heat release rate does not diverge from the predefined which means that a complete combustion is taking place, see diagram 8.16.

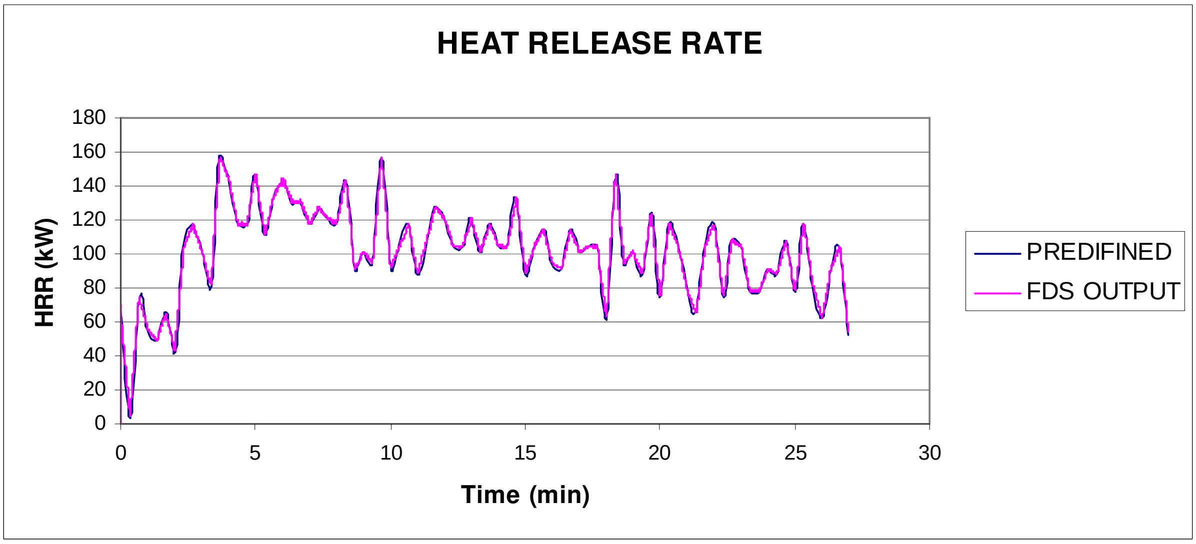


Diagram 8.16: Comparison between the predefined heat release rate and the FDS output (Case 7).

The oxygen level does, however, differ from the experimental results, see diagram 8.2, where the oxygen level is lower in the simulation.

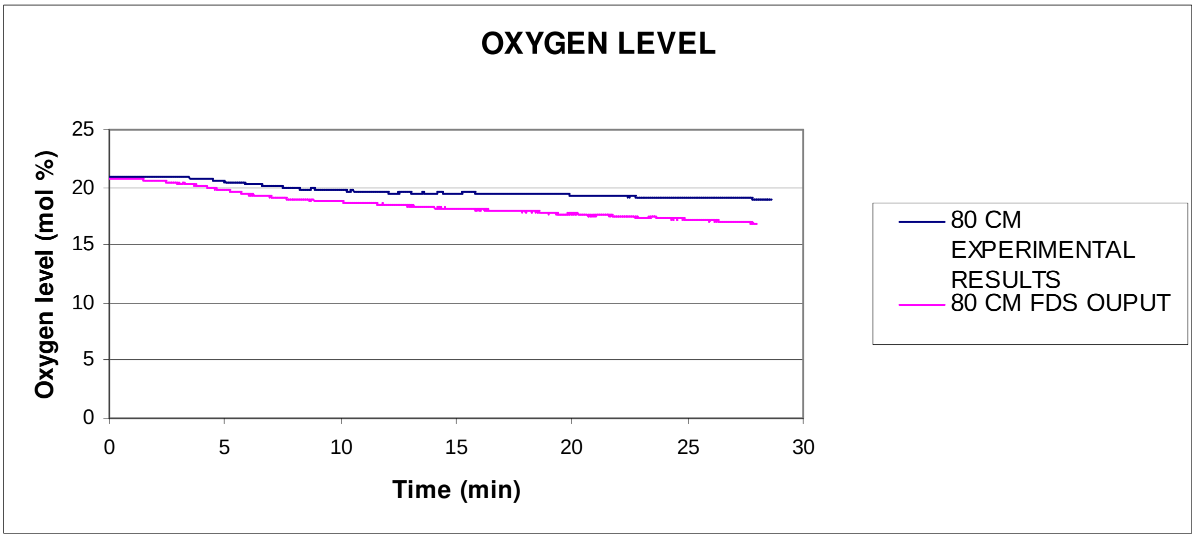


Diagram 8.17: Comparison of the oxygen levels (Pos 11, Case 7).

This does not affect the heat release rate since the oxygen level stays above any ventilation controlled oxygen levels, see diagram 8.1, but can be important in other aspects. The difference in oxygen level is around 5 % and the temperature difference around 5-15 %, see for example diagram 8.18.

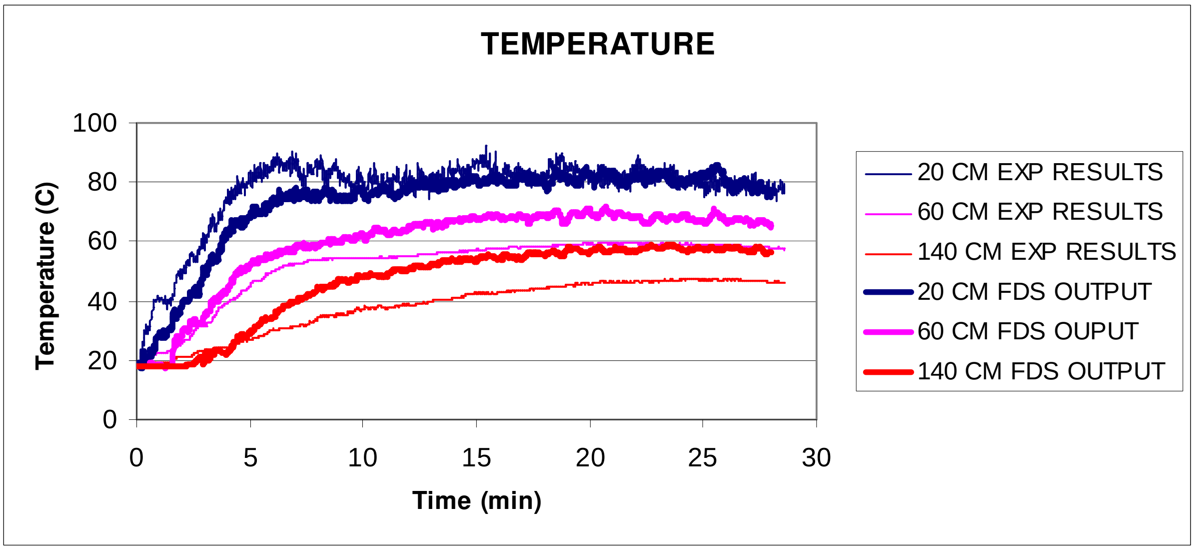


Diagram 8.18: Comparison of the temperatures (Pos 7,Case 7).

Case 10

In case 10 the heat release rate diverges from the predefined after about four minutes, see diagram 8.19. The heat release rate is after four minutes about half of the predefined (complete burning).

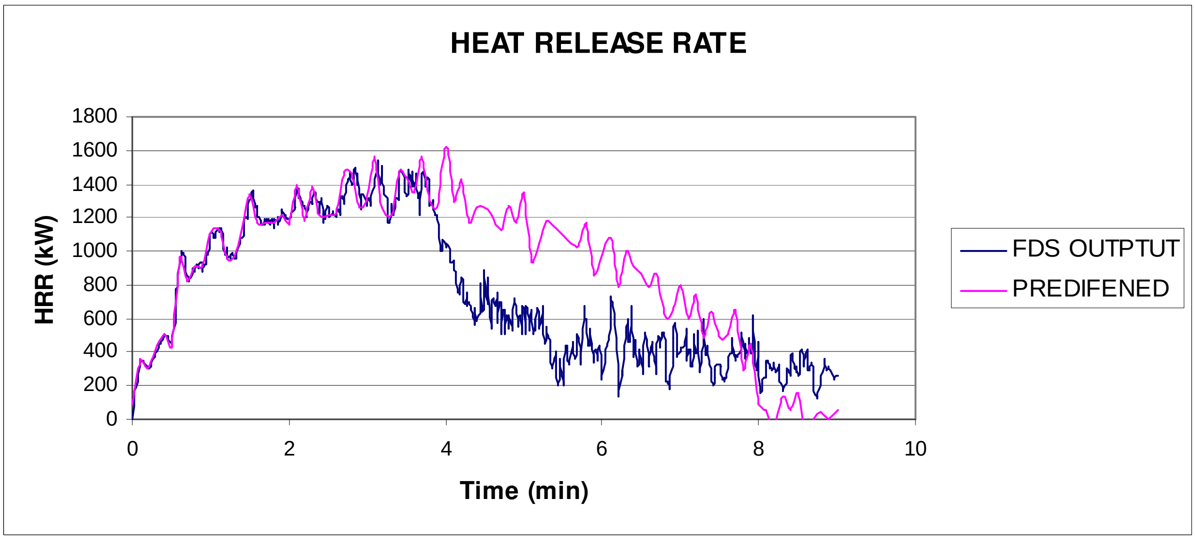


Diagram 8.19: Comparison of the heat release rates (Case 10).

The oxygen level diverges almost at once and after approximately 4 minutes it reaches the “no burn zone”, compare diagram 8.20 and diagram 8.1. The oxygen level described in diagram 8.20 is given for position 11 but the oxygen level is approximately the same in the near field of the fire (in the simulation).

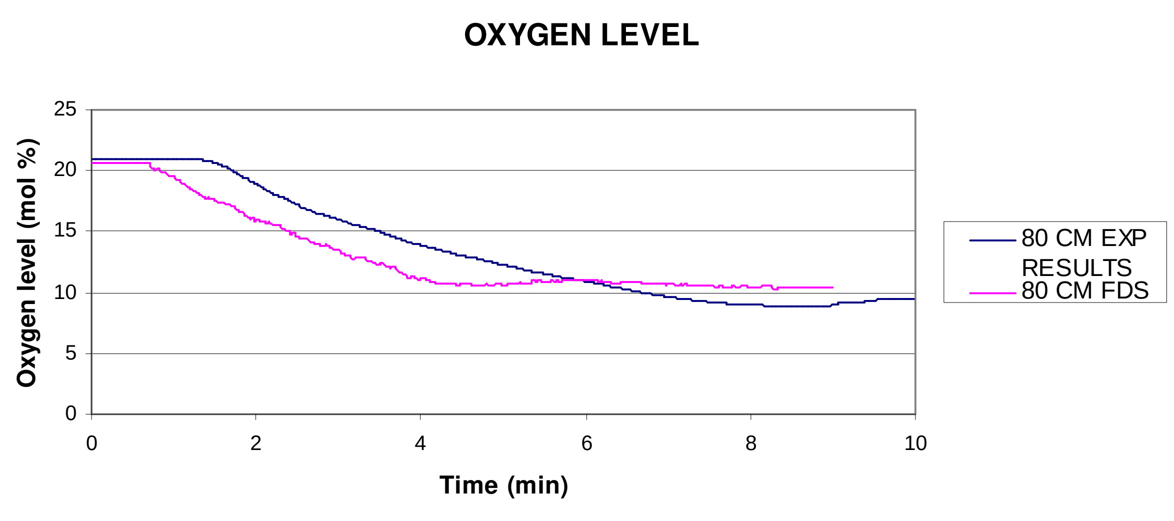


Diagram 8.20: Comparison of the oxygen levels (Case 10).

The FDS output HRRPUA (Heat Release Rate Per Unit Area) shows that the fire is struggling to survive after about four minutes and that it goes out at fuel source after about six minutes. After six minutes the burning takes place in the openings at the bottom of the short walls. This is, however, not the case in the experiments where the fire is ventilation controlled but still burn at the fuel source.

In the first four minutes, where the results indicate no direct ventilation limiting effects, the temperature in the upper region of the enclosure is approximately 250-300 °C. The lower part of the enclosure has a temperature of approximately 100-150 °C. The oxygen level differs with around 20 % and the temperature differs with around 10-20 %, see diagram 8.21.

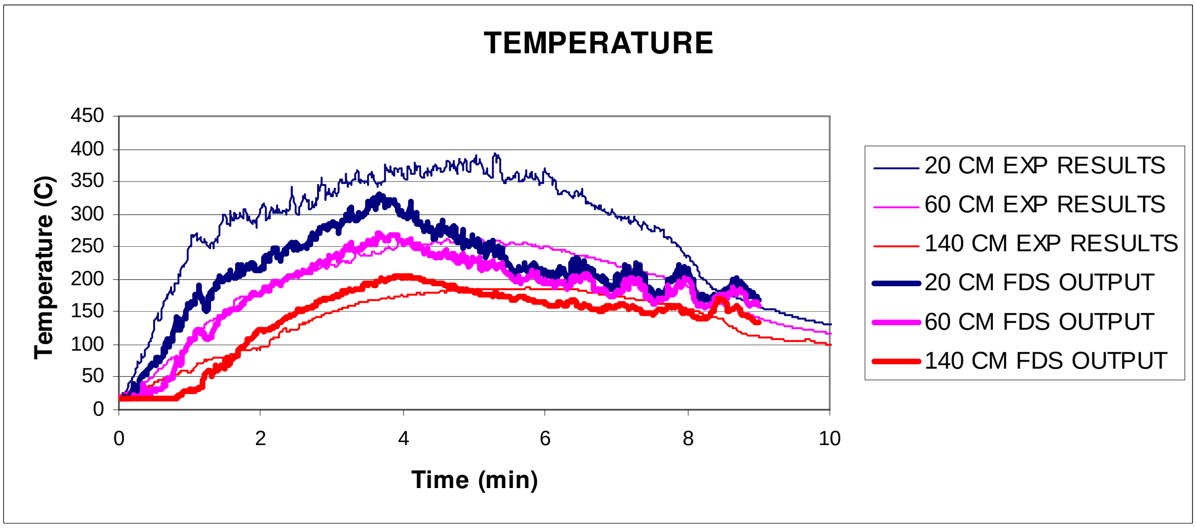


Diagram 8.21: comparison of the temperatures (Pos 7, Case 10).

8.5.3 Sensitivity and error factors

In section 8.4.5 the uncertainty and error factors in the experimental results were estimated by comparing different measuring devices and different tests. To try and estimate the uncertainty and errors involved in the FDS simulations sensitivity analysis were performed. There are many factors that can affect the results but they can be divided into two groups. The first is related to computer or computational error in which also errors due to the code is included. The second is related to scenario specific assumptions. Throughout the sensitivity analysis it is only case 10 that will be simulated since case 7 never reach under-ventilates conditions.

Computational error and sensitivity

The base scenario was a parallel calculation so a serial calculation was also done to check for any differences. The results are shown in appendix F and show that the difference in the oxygen level and the temperature are around 2-5 %. The heat release do however differ about 50 % at some specific moments, see diagram F 1, the reason for this is most likely a small difference in oxygen level. The difference in oxygen level is in the area of 11 -12 mol % (of the output, not difference) which is an interval sensitive to change. It is most likely that the fuel burn at 12 mol % but not at 11 %.

To be able to run the calculations as efficiently as possible the volume including the fire and the volume above the fire were divided into two different meshes (the base scenario). This is “necessary” since it is more efficient to have one mesh on each computer core. The FDS user guide states that it is not wise to put mesh boundaries in sensitive areas because the turbulence may not be accurately described in the transition between the meshes. Therefore, one simulation was done with just one mesh in the fires near field (instead of two), the results are presented in appendix G. The results show a difference of about 5-10 % for the oxygen level and the temperature. The heat release rate diverge with about 25 % for a short while.

Near the fire there are more complex phenomena e.g. more turbulence. This is the reason why a fine grid resolution is wanted in the near field of the fire. The size of the finer mesh in the near field of the fire is then important since complex turbulence phenomenon is best resolved in the finer mesh. Therefore a simulation is performed where the mesh size in the near field of the fire is smaller than in the base scenario. The results are presented in appendix H and show a difference of around 1 % for the temperatures and the oxygen level, even the heat release rate show a good resemblance and does only diverge once with about 30 % for a short while.

The base scenario used unsynchronized meshes and the FDS user guide states that there is a lesser connection between the meshes then when using synchronized meshes. To test for any difference, a simulation was done with synchronized meshes. The results can be viewed in appendix I and show that there is very little difference (less then 1 %) for the temperatures and the oxygen level. For the heat release rate there is a difference of about 30 % for a short period of time after about five minutes. This is most likely an effect of difference in oxygen level which can be viewed in diagram I 2.

The scenario was also simulated with different grid sizes where the base scenario had about 600 000 grid cells with 5 × 5 × 5 cm in the near field of the fire and 10 × 10 × 10 cm in the far field. In the grid sensitivity analysis, the grid size were halved which increases the total number of grids with a factor eight (8n) resulting in around 4 800 000 grid cells. In the sensitivity analysis the grid cells were 2.5 × 2.5 × 2.5 cm in the near field and 5 × 5 × 5 cm in the far field of the fire. The results are presented in appendix J and shows that the difference in oxygen level and the temperature is between 5-10 %. The heat release rate differs about 40 % for a short moment after about 5 minutes. This can also be explained by a difference in oxygen level in a sensitive interval (mol %). In this case the oxygen difference is bigger then in the earlier sensitivity analysis. The difference between the base scenario (n) and the 8n scenario can be explained by that the temperatures are calculated as an average of the entire grid cell. A large grid cell may therefore have different concentration in different parts of the cell that is not resolved. When the grid resolution is set finer then different concentrations, which existed in the large cell, can be resolved in just the small (fine) grid cell. If for example one large grid cell contains two equally large concentrations volumes, where the oxygen level in one volume is 5 vol% and 15 vol % in the other, then the average oxygen level is 10 %. When the grid resolution is set finer and the two different concentrations volume ends up in one grid cell each, then there is one grid cell with 5 vol% and one with 15 vol% which means that one of them may burn while it would not have in the large cell (10 vol%). These small ”pockets” of higher oxygen level is not presentable in a slice file. By using the HRRPUA (Heat Release Rate Per Unit Area) for all meshes this phenomenon can be observed, see figure J 1. The simulation is not grid independent but the results are still usable and the difference is not so big that conclusions cannot be drawn from the results.

Scenario specific assumptions

When it comes to scenario specific assumptions for under-ventilated fires then the soot yield and the carbon monoxide yield are important. They are extra important since they are two of the dimensioning parameters that can be used to assess critical conditions (visibility and toxicity). Soot and carbon monoxide yield are strongly affected by the combustion efficiency i.e. the oxygen level. The soot yield can increase with a factor five while the carbon monoxide yield can increase with a least a factor 50 when the fire gets under-ventilated (Tewarson 1995). The soot and carbon monoxide yield are directly specified by the user and the production rate (in percent) stays the same independent of the combustion efficiency. The ideal would be that the production rates could be changed over time in FDS. The new two step reaction function in FDS 5 can predict the carbon monoxide but the validity of this function can not be compared because of lack readings in the experimental data.

The simplification of no leakage from the room can lead to a higher pressure since there in the reality always are leakage through small cracks. The higher pressure will not have a big effect but what can have an effect on the oxygen level is where the leakage areas are situated. If they are situated in the upper region then it is the combustion products that leak out. If the cracks are situated below the smoke layer then air and oxygen leak out. The leakage has not been specifically investigated but is visually estimated to be small which is to some degree is confirmed by the velocity measurement comparison.

Other parameter that effects the validation of FDS for under-ventilated fires is the predefined mass loss rate or mass loss rate per unit area (MLRPUA). FDS assumes perfect combustion of the fuel vapour, if the MLRPUA is lowered then that is approximately the same as controlling the effectiveness of the combustion. Therefore, a simulation is performed where the MLRPUA is multiplied by a factor 0.7, which is a more realistic combustion efficiency. The results, see appendix K, indicate that the temperature in some measuring points is lower then in the experimental test. The difference is around 5-10 % for both the temperatures and the oxygen level. Once the fire has gone out the difference is about 20-30 %. The fact that oxygen level start to decrease earlier then the experimental results is still present but when the oxygen level nears the no burn zone limit the difference is smaller then with perfect combustion.

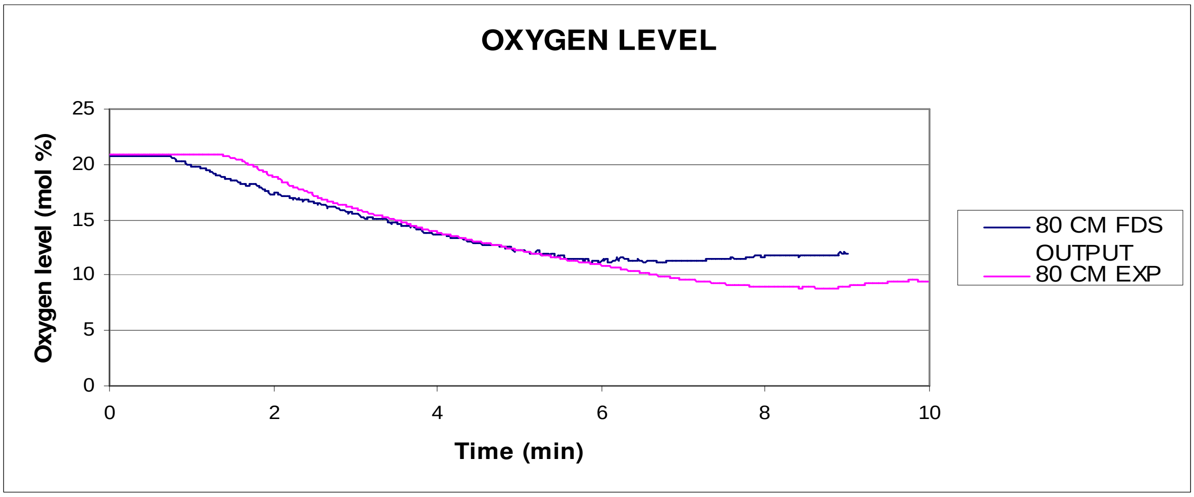


Diagram 8.22: Comparison of the oxygen level for case 10.

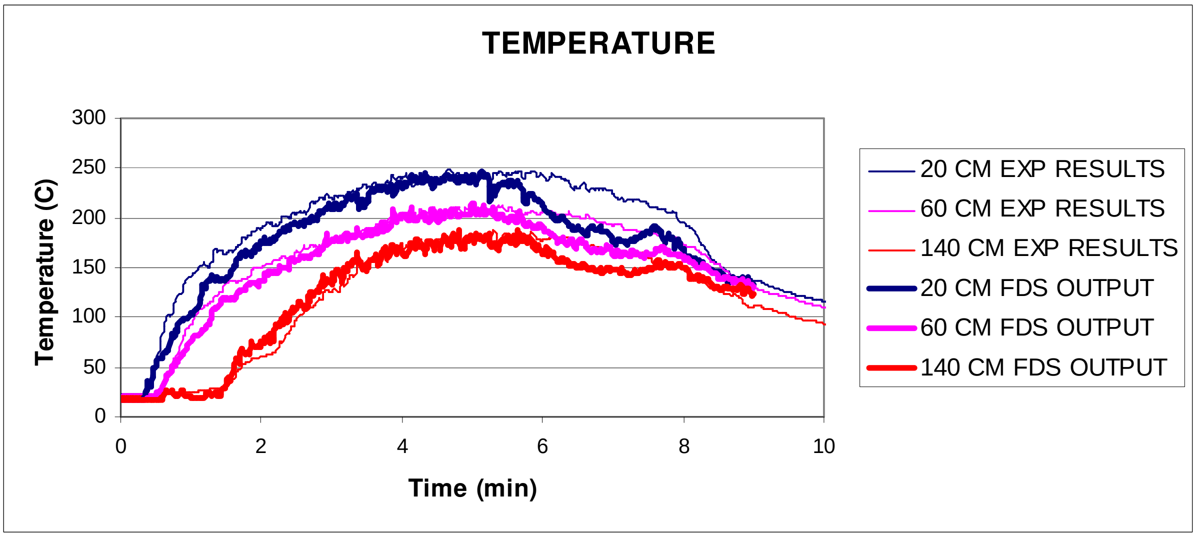


Diagram 8.23: Comparison of the temperatures for case 10 with 0.7 mass loss rate (Pos 16).

8.5.4 Discussion

Case 7 shows no signs of being ventilation controlled and the output matches the experimental results quite well with a difference according to section 8.5.2. The difference between the temperatures in the experimental and the FDS results are about 10-20%. If, however, the combustion efficiency would have been lowered, like in case 10, then the temperature would probably have an even better match.

It is important to note that the predefined heat release rate was not the actual heat release in the experiments, but only the heat release with a complete burning.

The results for case 10 show that the difference in oxygen level and temperature is about 5 % with a combustion efficiency of 0.7. When the fire reaches the no burn zone the difference in the oxygen level is about the same but same (5-10 %) while the difference in temperatures increase to about 30 %. The reason for this is because of that the heat release rate is strongly dependent and very sensitive to changes in oxygen level near the no burn zone. The difference in heat release rate is for a long period of time (4-5 minutes) underestimated with about 30-60 %. This is an effect of that the mixture fraction combustion model assumes a perfect combustion.

The sensitivity analysis shows that a difference of about 10 % in the temperatures is common due to different configurations. In the experimental results that "uncertainty" factor is also about 10 %. This means that for the temperatures, in the ventilation controlled stage, the difference between FDS and the experiments are 30 % but it could be any number between 10 to 50 % and for the oxygen level 0-30 %. To decide whether or not the intervals of difference in oxygen level (and by that the heat release rate) and temperatures above are acceptable or not it must be put into relevance. In this case the difference of 30 +/- 20 can create non conservative results since the fire can reaches the no burn zone earlier then in reality. A difference of 10 % is not a big difference when describing such a complex phenomena as a fire. A difference of 50 % points out that if the temperature is used as a critical parameter, when having an under-ventilated fire, it should be used with caution. This needs to be placed into relevance with other uncertainty parameter in a design. In an under-ventilated fire it is most likely the visibility or the toxicity that reaches critical levels first. The uncertainty and difference between FDS and the reality related to those parameters have not been specifically investigated in this report but is most certainly higher then for the temperature. If put into a bigger perspective the choice of probable fires and their locations is combined with even higher uncertainty. The difference and the uncertainty are in other words relatively big and should be used with caution but on a larger perspective the uncertainty in other parts of the dimensionings is greater and diminishes the importance of the difference in temperature.

As described above, the visibility and the carbon monoxide concentration are dependent on the soot and carbon monoxide yield specified by the user. With the normal combustion model they do not change (in percentage) over time with the combustion efficiency. For the carbon monoxide concentration there is a new function in FDS 5 that allows for a two step reaction which can track the carbon monoxide change over time. Unfortunately the experimental data lacks readings of the carbon monoxide concentration which makes any comparison impossible. Readings do however exist for the visibility i.e. the soot-yield output. The soot yield can, however, not be changed (in percentage) over time but is constant. If yields for carbon monoxide and soot are used for well-ventilated conditions then this will lead to non conservative results since the “yields” in reality becomes much higher in an under-ventilated fire.

The question is then how under-ventilated fires should be treated? The most crucial parameter is the combustion efficiency which governs when if oxygen level starts to decrease at the same in the simulations as in the reality. This can be hard to estimate since it is not only a matter of the properties for the fuel but also for the geometry of the enclosure. Even if the combustion efficiency is set to its optimal it still does not solve the problem of giving good results for the soot yield and the carbon monoxide yield. This is the case since only one yield can be set and cannot be made time dependent, it is the same soot yield the entire simulation even if it first is well-ventilated and then under-ventilated. Therefore the use of the visibility and the toxicity in an under-ventilated fire should be used very carefully. This is a problem since they are the most likely parameters to reach critical levels first in an under-ventilated fire and therefore “should” be used as a critical parameter. Therefore, when an under-ventilated fire is the case in a dimensioning the output should be used with caution since it is related to a big uncertainty, which later in the dimensioning when the conclusions are drawn and the consequences are taken should be handled with big uncertainty measures.

There is a function in FDS for dealing with leakage but it demands that the room is completely sealed with no openings. Therefore, the validity of this function could not be tested against the SP tests since there were openings in the walls.

To investigate how FDS track the carbon monoxide level with the new two step reaction experiments should be done with a measurement of the carbon monoxide level.

8.6 Conclusion

The comparison indicates that FDS easily can underestimate the oxygen level and thereby the heat release rate which in its turn creates an underestimation of the temperatures. The difference for the temperature is about 30 % but with an uncertainty factor of 10 % in both the experiments and the computer modelling the difference may be anywhere between 10-50 %. The validation has shown that the simple empirical expression for when the fire is allowed to burn is very sensitive and if used without proper handling it may produce bigger differences. It is clear that the temperatures may be underestimated and that the use of visibility and toxicity (soot and carbon monoxide yields) are related to even bigger uncertainties. If used in a fire safety design it is possible that incorrect dimensioning may occur because of incorrectness in the code. Since the temperature, the visibility and possibly the carbon monoxide level may be underestimated, with the consequence of that incorrect fire dimensioning may be non conservative.

For the visibility and the carbon monoxide level a comparison has not been possible and experimental data for carbon monoxide is necessary for under-ventilated fires so that the new two-step reaction can be validated.

The fact that FDS describes under-ventilated fires poorly and that it may under estimate the heat release, results in risks for incorrect dimensioning of a buildings fire and safety design.

9 User Handling

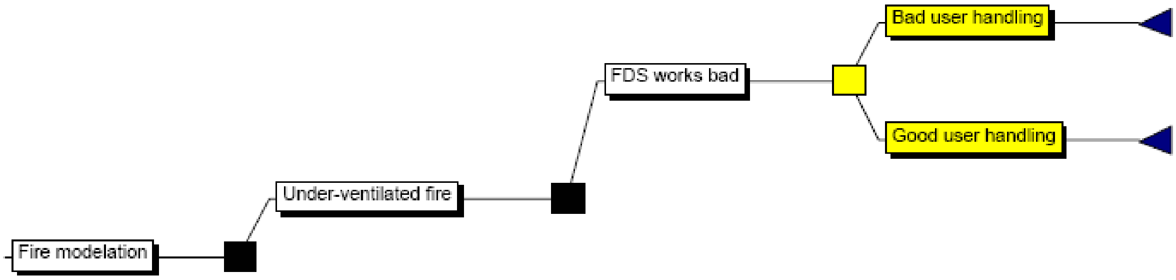


Figure 9.1:Third branch of the event tree .

The next branch in the event tree is how the users handle FDS for under-ventilated fires. Even if the code does not handle under-ventilated fires in a good way it is first when the user "introduce" the error that it might lead to incorrect design. If the users are aware of how the program treats under-ventilated fires, and other affecting factors, the importance of the error can be diminished (for example by adding safety factors) and thus resulting in a low possibility for incorrect dimensioning of buildings fire and safety design.

How the user handles under-ventilated fires in FDS is dependent on many different factors but the three requirements below is needed in every dimensioning.

1: FDS knowledge

The users have to have a good understanding of how FDS works so that good results may be produced.

2: Background knowledge

The users have to have good knowledge of the underlying physics e.g. fire dynamics and CFD.

3: Process and results handling

The users have to handle the modelling process and the output in a good way

These three requirements have been "selected" because form the basis for every FDS modelling. The first requirement is obvious to know how FDS works. The limitations and the assumptions of the sub models are important and if the user do not understand them then the user may "introduce" errors. The users also have to have good knowledge about physics and CFD to be able interpret and critically view the results. If they do not posses this knowledge the output may be used in an improper way. The third requirement is perhaps less obvious then the two first but if the output is handled in a bad way, e.g. dismissing contradicting data due to subjectivity then the design can be incorrect. Quality checks is also an important part of the modelling process, if they are performed then errors are less likely to occur.

To identify if the users in Sweden have the qualities above an interview survey was done. The respondents were fire safety consultants in Sweden, see chapter 5 for the interviewing method. To get sincere and good answers from the respondents they were assured anonymity. The answers have been summarized in appendix A. The interview sheet in appendix A contains several questions to which very few holds direct answers to the requirements above. Therefore several questions may together give an estimation. In an interview it is not only information in the direct answers that can give results but by reading between the lines the interviewer can receive a lot of information. This is very hard to document and present in a scientific way, see chapter 12 for discussion of used methods.

1: FDS knowledge
To check for the users understanding of FDS is more difficult then to check if they have a good understanding of fire physics and CFD. This is the case since there are no direct FDS courses available, in the CFD course at Lund University FDS is used but there it is still self-learning that is the basis. When the consultant starts his or her professional work with FDS knowledge about the handling can be limited especially for many of the sub models. In this report it is investigated what knowledge the user has for under-ventilated fires. To check this an open question was asked: "*How does FDS treat under-ventilated fires and how do you deal with that*". The question is very open and the answers were expositions of different depths. However, only one of the respondents knew how FDS works for under-ventilated fires. Most did not check the output files for indications but some checked the heat release rate. Some were also of the impression that under-ventilated fires never happens and therefore do not need to be considered. Another alarming fact is that the users generally seem to use the visibility and toxicity as output. This can be dangerous when the fire becomes under-ventilated since a real fire increases the soot and carbon monoxide production several magnitudes once they turn ventilation controlled.

It is not only the users understanding of under-ventilated fires that can introduce errors but also the basic use of the program e.g. putting up the meshes, describing materials etc. This is hard to check through a survey and should best be checked by reviewing used script files. Unfortunately this has not been possible and the user's skills are only mapped through the interview. In the interview there were basic questions asked about running a FDS but also the total impression of the interview. This is very hard to present in a scientific way but the overall impression is that running of simple well-ventilated fires is handled in a good way.

2: Background knowledge
Whether or not the users have a good knowledge about fire dynamics and other basic physics is investigated by asking the respondents what kind of education they had. Close to 95 % of the employees who worked with CFD at the agencies who participated in the survey were Fire and Safety Engineers graduated from Lund University. A Fire and Safety Engineer from Lund University is considered to have good knowledge about basic fire physics, at least to such an extent that he or she can critically view the results for smoke spread issues in enclosures (if nothing else showed in the interview).

To check if the users have a good understanding about CFD, questions were asked about what kind of CFD-education the users have but also through asking about basic CFD problems. Close to 85 % of the employees working with FDS have taken the basic CFD course given at the Department of Fire Safety Engineering and Systems Safety. The rest had learnt it at a research institute (SP or FOI) or were internally educated. All the employees who had taken the Lund University CFD course were also Fire and Safety Engineers. A Fire and Safety Engineer who has taken the CFD course is considered to have good knowledge about CFD. Employees with background at research institutes can also be considered to have a good understanding about CFD. People who are internally thought is not considered to have a good knowledge about CFD. This because they are trained to get the program working with out knowing the background facts about CFD.

3: Process and results handling
Even if the user would have a good knowledge about the two steps above it is still important that the consultant is as objective as possible and looks rationally at the results. The consultant is always hired to find a solution to a problem and economical aspects are involved. This can create a problem since the user may look for output that verify his or her theory and neglect contradicting data. There is no easy way to estimate the impact of this since it requires a thorough analysis of output data and how the user interpreted them under the specific circumstances. In the survey an attempt to capture some of the problem was made by asking how much of a roll the client's intent has. The general method amongst the fire safety consultants were to do an estimation if the problem could be solved before actually simulating it. This approach reduces the likelihood of an incorrect dimensioning since there is little data that can be miss interpreted (since the scenarios that are impropriate for simulating is not

simulated). Some answered that the satisfying of the customers might affect the results. This question is perhaps the hardest question for the user to answer sincerely since the respondents might not want to admit the subjectivity.

It is also important that the agencies perform internal quality checks so that eventual error may be corrected. This is examined both by looking at how many FDS-able persons there are in every agency, the more people the higher possibility of a quality check. Close to 90% of the agencies in the survey had at least two FDS able persons employed. The agencies also have a legal and economical responsibility if they do an incorrect dimensioning, a common answer in the interviews were that they would not hand over a dimensioning that they were not sure was accurate. The working process in about half of the agencies were done in groups which also reduces the possibility of incorrectness.

Conclusion

The fire safety design consultants generally seem to have the knowledge about fire physics and CFD that is needed to be able to look critically at their results. They do, however, not seem to have a good understanding about how FDS works for under-ventilated fires and that the output parameter for visibility and toxicity (carbon monoxide) is strongly linked to the soot yields which in its turn is strongly affected by if the fire is under-ventilated or not. The users seem to be able to handle basic FDS set up in a good way. An eventual error in the project set up is most likely picked up in the quality check that is done on a regular basis. The quality check is, however, linked with the problem that the quality checker only can find errors where he or she has good knowledge. In other words a quality check is likely to spot simple and common errors but where there is shortage in knowledge e.g. for under-ventilated fires, then this can be missed. The problem of that the consultants may not look critically enough at their results, in an attempted to satisfy their customers, is not fully clarified but the interviews show that the consultants does not hand away a dimensioning of which they are not sure about the results. A common approach was to first do an estimation of the problem before simulating. However, some still answered that the subjectivity can affect the results.

In total is likely that incorrectness in how FDS simulates under-ventilated fires is missed by the Swedish fire and safety consultants. This is related with that the user have a poor understanding of how FDS work for under-ventilated fires along with the use of visibility as a critical parameter.

10 Reviewer handling

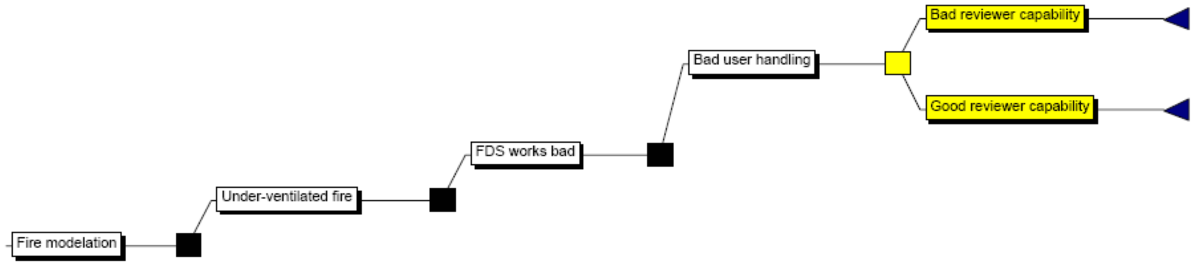


Figure 10.1: Fourth branch in the event tree..

When an analytical dimensioning is the case in building project it is up to the future proprietor (Byggherre) to ensure that the fire safety standards are met (9 chapter 1 § PBL). The future proprietor usually lay this task upon the fire and safety design consultants internal quality checks (egenkontroll) although the responsibility still lie with the future proprietor. The local building board (Byggnadsnämnden) is responsible for the municipal's tasks within construction (1 chapter 7 § PBL) and at the building consultation meeting they decide whether or not the future proprietor's control system (in this case the amount of verification) is sufficient. If local buidling board is not capable (almost always) of making that judgement they may use a referral instance which most often is the fire and rescue service. The purpose is not that the rescue service should be a second dimensioner but just suggest the amount of verification (control) that is needed. In recent years it has, however, been acknowledged some serious shortage in the future proprietors internal checks (Lundin 2005). Many rescue services have therefore expanded their role and do often stand as an unofficial quality checker of analytical dimensionings. To check how the rescue services handle their "role" as a reviewer, and the level of their knowledge, a survey consisting of telephone interviews were conducted. The general approach was to try and examine three different factors:

1: Handling process
To what extent and how does the rescue services receive the fire safety design?

2: Knowledge
What is their capability of doing a good review especially for under-ventilated fires?

3: Resources
What is their reviewing technique?

The first factor has been chosen since it is important when the reviewing takes place in the building process. If the rescue service is involved in an early stage, which can be the case when the rescue service and the local building board has a close cooperation, then the incorrect dimensioning can be detected earlier which simplifies the building design process. Factor two is quite obvious, if the rescue service does not have the knowledge to do a review then incorrectness can be hard to identify. Factor three is dependent on the resources the rescue service has to do a good review.

1: Handling process
How the rescue service receives the analytical design varies a lot and is decided on local conditions. In 30 % of the rescue services in the survey the rescue service and the local building board have a close cooperation. About 70 % of the rescue services do not have a close cooperation and just work as a referral authority. How often the rescue services receives a dimensioning is much dependent in what region of Sweden they are situated. The large rescue services i.e. in the bigger cites around 15 to 30 a year dimensioning a year but in smaller rescue services the number is around one to three a year.

2: Knowledge

The capability amongst the rescue services is varying but they do generally have a Fire and Safety Engineer (about 90 % in the survey) in their staff. Depending on the size of the rescue service they have more or less engineers employed. If a Fire and Safety Engineer is employed then the analytical dimensioning review is made by an engineer. In 70 % of the rescue services, which has a Fire and Safety engineer, the employee also had CFD knowledge trough the CFD course given by the Department of Fire and Safety Engineering and Systems Safety. No one in the survey knew how FDS worked for under-ventilated fires but some were under the impression that it works poorly.

3: Resources

The reviewing technique also differs and follows no standard or set up rules but is instead decided by the resources (time and staff). About 80 % of the interviewed only looked at the input parameters and the discussions in the documentation that follows with the dimensioning. Reviewing of direct simulation output or resimulation is almost never performed, mostly because of lack in time and computer power. Another strategy (the remaining 20 %) is to review the designer once and if every thing seems fine then they trust that future dimensioning also will be good.

When there is more then one Fire and Safety Engineer they work in groups. In the rescue services that do not have qualified personnel, informal networks are used such as friends from the Fire and Safety Engineering programme or someone outside the rescue service but inside the region.

Conclusion

The capability, on a personnel level, to review analytical dimensioning in general seems to be good. In almost every rescue services there are Fire and Safety Engineers. They do however lack in knowledge when it comes to how FDS treats under-ventilated fires. A “resource” that is generally missing is time, very few had time to review the output and the most common way to review were by looking at the input. It is hard to do a good review by only looking at the input especially for under-ventilated fires. For under-ventilated fires the geometry and openings to surroundings plays a big role which can be hard to get a grip of by just looking at the input. When the reviewer at the rescue services judges that they are not capable to do a review they apply informal routines and ask people that they trust are capable to do a good review.

In all, although the rescue service does not have the legal right to work as an executive reviewer this is often the case. Even if there are a lot of a Fire and Safety Engineers working as reviewers it is still probable that incorrectness in how under-ventilated fires are simulated and handled by its users is missed by the reviewers. This is related to that reviewers lack in knowledge but also that they do not have time to review the output just the input. About the possibility of missed incorrectness in a dimensioning it can be said that if under-ventilated phenomena is not captured by the consultant, it will not be discovered by the reviewer.

11 Risk related to the use of FDS for under-ventilated fires

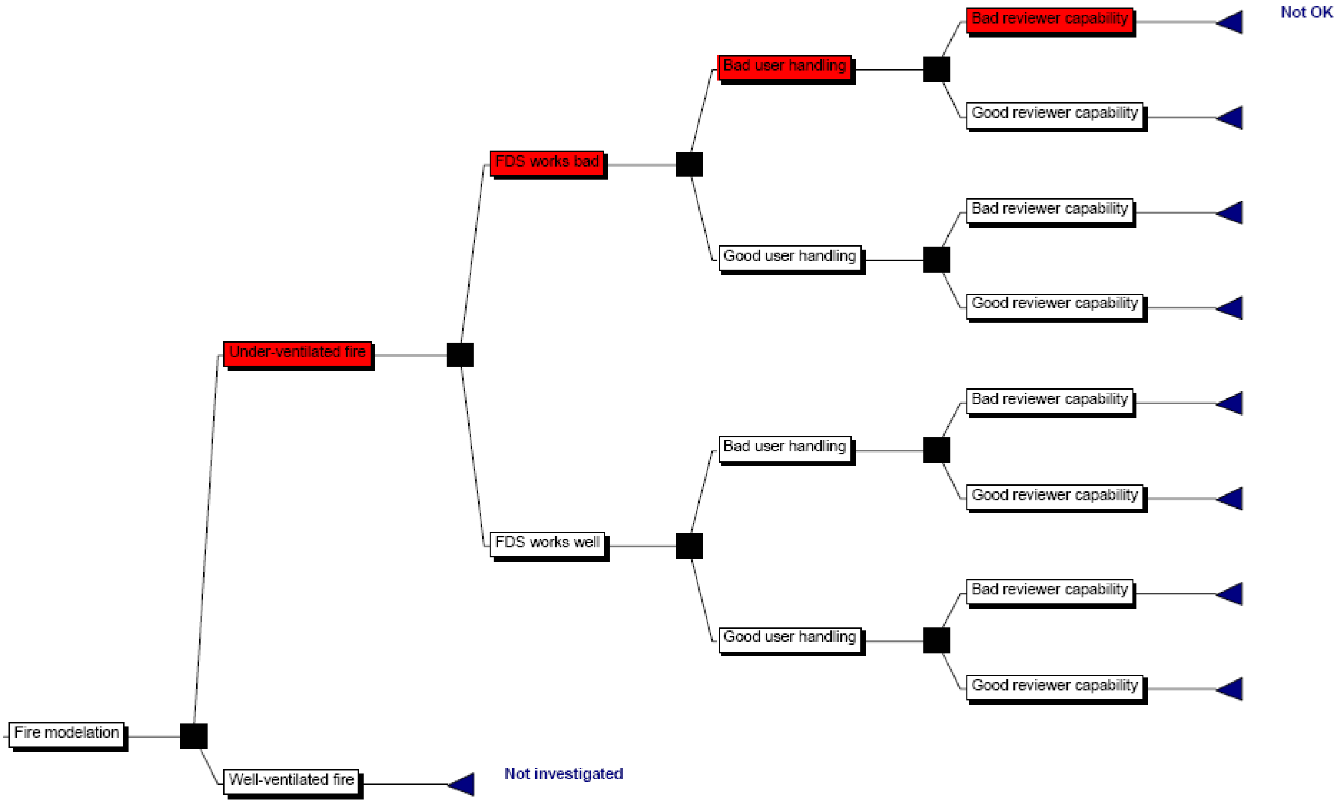


Figure 11.1: The event tree.

One of the overall goals was to check if possible incorrectness in how FDS simulates under-ventilated fires constitutes risks of incorrect fire safety design in buildings. In the report this is done through four different sections. This is shown schematically in the event tree above. The red chain of events are the circumstances that actually exists and the other branches are not “valid”.

The first step clarified that under-ventilated fires are especially hazardous due to the amount of carbon dioxide and soot concentration they produce. This indicates that the consequence might be high if FDS does not simulate under-ventilated fires in a good way. The chapter also clarified that under-ventilated fires are likely to be simulated on a yearly basis in Sweden.

The second step was to see how FDS handles under-ventilated fires. The results of the validation show that the combustion model, with its empirical expression for when the fire is allowed to burn, is very sensitive to changes in the oxygen level where the fire may not burn in the simulation whilst it would have done in the reality. This means that unconservative results can be produced. Another source of error can be ascribed to FDS’s simulation capabilities of carbon monoxide and soot production. The new function in FDS 5 for tracking the carbon monoxide production has not been validated. The formation of soot or the soot yield, that is the base for the visibility output function, does not change over time. The soot production is strongly correlated against the combustion efficiency but this cannot be simulated in a good way in FDS, the soot production can be non conservative if the user specifies a soot yield for a well-ventilated fire. This means that if the user does not handle FDS well for under-ventilated fire then that can create incorrect and hazardous fire and safety design in buildings.

The next step was to examine the user handling of under-ventilated fires in FDS and see if the incorrectness described above can create incorrect dimensioning in buildings. In the survey it is clear that fire safety design consultants in Sweden generally have a good basis in fire physics such as fire dynamics. The users also have a good understanding about basic CFD. The users do, however, not have a good understanding about how FDS simulates under-ventilated fires. The users also frequently used the FDS output for visibility and carbon monoxide which by how FDS works is very hard to simulate properly for an under-ventilated fire, with non conservative as a result.

The last step was to examine the reviewer's capability to do a good review so that possible incorrect dimensioning by the consultants is captured and not "used" in buildings. The results of the survey show that even if there are many Fire and Safety Engineers working in the different rescue services there are few, if none who has the knowledge about how FDS works for under-ventilated fires. This means that if a consultant uses FDS in an "incorrect" way for an under-ventilated fire it will not be discovered and stopped by the reviewer at the rescue service.

The total series of events are illustrated in the event tree above where the red trail is the events or circumstances in the process of modelling under-ventilated fires with FDS in an analytical dimensioning of a fire safety design in buildings. In total: the conditions that can arise in an under-ventilated fire and the way that FDS simulates this, along with that the users and the reviewers have a poor understanding of how FDS handles under-ventilated fire can create incorrect fire safety design of buildings, that effect the conditions for people's health negatively in case of a fire. This means that people during an eventual fire in a building may be exposed to hazardous conditions (in addition to the "normal" level) due to the incorrect fire safety design, such incorrect dimension is likely to occur on a yearly basis in Sweden. The question of acceptable risk level is not brought up in this report which has to do that the risks need to be put into relevance. The comment "Not OK" in the event tree just clarifies that the chain of events or circumstances leads to incorrect fire safety design which can expose people to hazardous circumstances in case of fire. There are of course other events sorrounding the dimensioning that also can create incorrect fire safety design in buildings but that is beside how under-ventilated fires are handled and therefore not investigated.

12 Discussion of used methods

Several of the sources of information in the report are produced by the author. The validation and the surveys are the information basis for discussions and conclusions and therefore needs to be criticized.

The validation
The experiments were performed by the SP Technical Research Institute of Sweden under Anders Lönnermarks supervision. The test series included several repeated tests to see if the results would match, with good results. Anders Lönnermark is senior scientist with long experience with experimental tests. The experimental data is therefore seen to be collected during best possible conditions.

A very important part of the validation are the simulations. The author is, at the moment, still a student and the question is if the author is qualified enough to perform the validation. The author is a graduate student from the Fire Safety Engineering program with background in fire dynamics, heat transfer, fluid dynamics and all the key physics in fire modelation. The CFD background is the basic CFD course given by the Department of Fire and Safety Engineering and Systems Safety with a focus on FDS. The author also works as a fire and safety consultant and constantly works with FDS in analytical designs. Despite this, the author cannot be seen as a "flawless" FDS able user. Because of that Professor Göran Holmstedt and Professor Patrick van Hees, both from the Department of Fire and Safety Engineering and Systems Safety, and leading figures in the application of FDS have been involved to ensure the quality of the work. Heimo Tuovinen at the SP Technical Research Institute of Sweden has also helped with the computer cluster.

User interviews
In the survey related to map the usage of FDS among fire safety design consultants in Sweden it is crucial who the respondents are. Contacts were made with most of the fire and safety consultancy agencies but only 9 agencies were mapped. The reason for that no more were interviewed was time restrictions. Nine agencies do however constitute a considerable part of the agencies in Sweden. Since not all agencies and therefore not all users were interviewed it is important that the ones that were interviewed reflect the others. Hence it is important that all sizes of companies are interviewed both small and large. This was the case in the survey and included companies that had worked with FDS for some time and those who just have got started. Within the companies there are consultants of different level when it comes to using FDS. This is a possible flaw in the survey since the author mostly interviewed the CFD/FDS responsible persons in the agencies, persons that can be expected to have a better understanding of FDS then some of the other employees. The most FDS crucial question in the survey was about the knowledge of how FDS treats under-ventilated fires, which most respondents did not know. This can be seen as "conservative" since there is not likely someone in the agency that have a better understanding.

The interview technique is also of importance and needs to be criticized. In accordance to the interviewing method in "Vetenskaplig Method (Ejvegård 2007) the interview started with expressing the purpose of the interview, the authors background as an student but also as an consultant. The author also ensured the respondents that the interview were anonymous and that their or their agencies name would not be mentioned in the report. The reason for this is to get as honest answers as possible. The author also ensured the respondents that the answers would stay in the premises of the report and that the author would not take the knowledge with him to a professional level, important for getting honest answers since the author work as an fires safety consultant and is indirect a business rival. The general interviewing technique was to ask open questions i.e. not leading questions, for example: "How do you build up your meshes" instead of asking "Do you build up your meshes overlapping or edge to edge". By asking in this way more information around the "core answers" can be found which often tells a lot about the respondent's knowledge. Therefore, there is a considerable amount of questions, more then have been brought up in the report. Much of the results from the survey are the overall impression of the interview. This is very hard to present in a scientifically good way. The direct answers are not always a good way since they may not contain the interesting fact. A summary of each interview is a possible way. The results in chapter 10 ad 11 are really summaries of the interviews that to some extent are based on quantification of interpretation of some of the answers. This should also be done with caution, for example when the knowledge about basic fire physics is surveyed the result is based on if the user is a Fire Protection Engineer. If the user is a Fire Protection Engineer then he or she is assumed to have good knowledge about fire physics. This does not have to be true but is a way to be able to get results, to really be sure that the user has a good understanding of fire physics then the user should be asked to perform extensive "exams" which has not possible to do. Therefore, to get any results the answers must be interpreted. The fact that a lot of the information, which discussions and conclusions are based upon, is interpreted by the user constitutes a risk since the author may have done a bad interpretation. Therefore, it is vital that as much of the material is gone through with the persons that stand as quality checkers for the report.

Reviewer interviews

In the survey for mapping the rescue service capability of doing a good review it is important to get the full spectra of the different sizes of rescue services. This is the case since about 20 % of the total rescue services were surveyed. The spectra of different sizes is seen as rescue services in: large cities (Stockholm, Göteborg, Malmö) and middle size cites or populated area (Linköping) and less populated area, which also was the case and the interviews. The interviewing technique was a little bit different then in the survey for mapping the user's knowledge. This was the case since the purpose here was not to try and map the total extant of their CFD and FDS usage but only their capability and available resources for reviewing. The questions are therefore more direct yes and no or very short answers like "What is your knowledge about CFD". It is however linked with the same uncertainties as above when it comes to the author's interpretation of the answers that lay as a basis for the discussions and conclusions.

13 Risk reducing measures

As expressed in the beginning of this report: the goal is on handling FDS and handling the risks that is related to its use in fire and safety design in buildings. Therefore the preventive measures in this section will also be on handling the risks. The risks would of course also be reduced if FDS in anyway would simulate under-ventilated fires in a better way but as described above the focus is on the handling.

The best way to reduce the risks of incorrect dimensioning in buildings related to the use of FDS for under-ventilated fires is to improve the handling of the users. By improving their handling the last step of the chain "the reviewer" becomes less important. The way to a better handling can be achieved in different ways. First, since almost every FDS working consultant has taken the basic CFD – course given by the Department of Fire and Safety Engineering at Lund University it can be expanded to contain more "teaching" about FDS. With the current design of the course much time is dedicated to the RANS-code program SOFIE. If the time spent on trying to learn SOFIE instead was laid upon FDS, then a better usage could be expected. An alterative to this could be to have a supplementary course with orientation towards the understanding and the usage of FDS.

Even if the basic CFD course is expanded to contain more elements about FDS it is still no guarantee for that the student actually learn more. Another approach to "secure" a good usage would be by certifying the users. The problems to be solved for this are many: Who should certify the user, what should the criteria be for a certifying, how should this be checked? Conceivable certifiers can be "trade organisations" such as BIV or Educational centres such as Lund University. A recommendable party is a trade organisation such as BIV, this because they may have a better understanding about the application of FDS in the "field" and capable of reviewing reasonable judgments. The system of having certified CFD users also makes the reviewers process easier. The reviewer's task is to examine if the consultant is capable of doing a good dimensioning. When certified users can be expected to have a greater knowledge or do a better dimensioning then the general user and since the rescue services knows this then they can redirect their resources to review design from those who are not certified.

Another approach could be to arrange user workshops were experiences could be exchanged. This approach are linked with the problem that all agencies might not want to share their knowledge since this can results in lost markets shares.

Another way to reduce the risk related to the use of FDS for fire safety design in buildings and under-ventilated fires is to improve the reviewing. Today there is a mix of internal checks and checks performed by the rescue service. The governing legislation can be questioned and should be evaluated. Is it wise to put all the quality check in the future proprietor hands? By giving the local building board legal responsibility to review analytical designs (who may use the rescue service as a referral authority) then both the future proprietors and the municipality's needs may be met. This is of course a very big change in the legislation since it is not only within fire and safety design in buildings that the control system lie in the consultants internal checks (egen kontroll) If it, however, were to be the case then the rescue service must be given the resources that is needed. Today there are a lot of Fire Protection Engineers working in the rescue service but they do not have the resources, most of all no time, to do a good review. A way to enhance the reviewer's capability could be by establishing one or several special groups that only works with reviewing analytical dimensionings who. In time they may evolve their knowledge and skills about CFD and FDS (amongst others). To follow the development of the programs is very important since there are constant changes. How many groups or personnel that are needed is of course a question about the amount of work load that can be expected. The initiative of such a group should be done by the Swedish Rescue Services Agency (Räddningsverket) or a combined effort by the different rescue services.

A mix of the three measures described above is of course favourable but most important is to improve the handing of the users.

14 Conclusions

The questions at issue were:

- How does FDS simulate an under-ventilated fire?
- Does possible incorrectness in how FDS simulates under-ventilated fires constitute risks of incorrect fire safety design in buildings?
- What can be done to reduce the risks?

The first question of issue was how FDS simulates under-ventilated fire. In the validation it is shown that the empirical expression for when the fire is allowed to burn combined with the mixture fraction combustion model makes the heat release and thereby the temperature very sensitive to the oxygen level when the level approaches the no burn zone. This creates a difference of approximately 30 % in the temperatures when the fire is under-ventilated but uncertainties in the experiments and the computer modelling is both about 10 % which means that the difference between FDS and the reality may be in the interval of 10 -50 % for the temperatures. The validation has also pointed out that there are other parameters that are combined with even bigger uncertainties e.g. the visibility (soot yield) and the toxicity (carbon monoxide).

The second question was to decide if possible incorrectness in how FDS simulates an under-ventilated fire constitutes a risk for incorrect fire and safety design in buildings. Through four steps (see for example chapter 11) it has been shown that the conditions in under-ventilated fires creates especially hazardous conditions for the visibility and the carbon monoxide level. In the validation it has been shown that there are incorrectness in how FDS simulates an under-ventilated fire, see section above. It has been shown that under-ventilated fires are likely to be simulated on a yearly basis and that the users (Fire and Safety consultants) generally have a poor understanding about how FDS works for under-ventilated fire. The reviewers (rescue services) also have a poor understanding about how FDS works for under-ventilated and also little resources for doing a good review. In total this means that incorrectness in how FDS simulates an under-ventilated fire do constitute a risk and that when used for fire safety design in buildings it may create a hazardous design.

The third question about reducing the risks is focused in the users handling of the program and the simulation and dimensioning process. Possible measures for improving the users knowledge about how FDS works for under-ventilated fire and how it affects the results is by adding more FDS-teaching at the basic CFD course at the Department of Fire and Safety Engineering and Systems Safety. There is, however, no guarantee that the students/users actually learn more. This could, however, be “guaranteed” by introducing certified FDS-able consultants, it is favourable that it is a trade organisation such as BIV who stands for this. Improving the reviewer’s knowledge about how FDS treats under-ventilated fires could be done by creating one or several specialist groups for the different rescue services.

Future needed work that is mostly for the validation process. A validation of the new two step reaction for tracking the formation of carbon monoxide is wanted. On a program code perspective it is favourable that a more advanced model for combustion is added so that under-ventilated fires may be more accurately simulated.

15 References

Written

ASTM, (2005), *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*: ASTM E1355-05a, American Society for Testing and Materials, West Conshohocke, PA, USA.

Axelsson J., Andersson P., Lönnermark A., Van Hees P., Wetterlund I., (2001), *Uncertainties in measuring heat and smoke release rates in the room/corner test and the SBI*, SP Rapport 2001:04, SP Fire Technology, SP Swedish National Testing and Research Institute, Boras.

Dittmer T., Jämtäng U., (2006), *Känslighetsanalys av FDS och dess undermodeller i ett tunnelscenario,* Department of Fire and Safety Engineering, Lund Institute of Technology, Lund University, Lund.

Ejvegård R., (2007), *Vetenskaplig metod*, Studentlitteratur, Lund.

Lundin, J., (2005), *Safety in Case of Fire – The Effect of Changing Regulations*, Rapport 1032, Department of Fire and Safety Engineering, Lund Institute of Technology, Lund University, Lund.

Kaplan S., Haimes Y.Y, Garrick B.J, (2001), Fitting Hierarchical Holographic Modelling into the Theory of Scenario Structuring and a Resulting Refinement to the Quantitative Definition of Risk, *Risk Analysis*, Vol 21, No 5.

McCaffrey B.J., Heskestad G., (1976), Brief Communications: A Robust Bidirectional Low Velocity Probe for Flame and Fire Application, *Combustion and Flame*, Vol 26, 125-127.

McGrattan K., Hostikka S., Floyd J., Baum H., Rehm R., (2008) *Fire Dynamics Simulator (Version 5) Technical Reference Guide*, NIST SPECIAL PUBLICATION 1018-5, National Institute of Standards and Technology, US Department of Commerce, Washington DC, USA.

McGrattan K., Klein B., Hostikka S., Floyd J., (2008b), *Fire Dynamics Simulator (Version 5) User Guide*, NIST SPECIAL PUBLICATION 1019-5, National Institute of Standards and Technology, US Department of Commerce, Washington DC, USA.

Rubini Dr. P, (2006), *SOFIE (Simulation of Fires In Enclosures)*, School of Engineering, Cranfield University, Cranfield, England.

Rubini Dr. P, (2008), Lecture: *An introduction to CFD*, Department of Fire and Safety Engineering and Systems Safety, Lund Technological Institute, Lund University, Lund.

Rubini Dr. P, (2008a), Lecture: *Credible CFD – Verification and Validation*, Department of Fire and Safety Engineering and Systems Safety, Lund Technological Institute, Lund University, Lund.

Rubini Dr. P, (2008b), Lecture: *An introduction to fluid dynamics*, Department of Fire and Safety Engineering and Systems Safety, Lund Technological Institute, Lund University, Lund.

Rubini Dr. P, (2008c), Lecture: *Turbulence – Phenomena and Simulation*, Department of Fire and Safety Engineering and Systems Safety, Lund Technological Institute, Lund University, Lund.

Rubini Dr. P, (2008d), Lecture: *An Introduction to Numerical Methods for Fire Simulation*, Department of Fire and Safety Engineering and Systems Safety, Lund Technological Institute, Lund University, Lund.

Tewarson A., (1995), *Generation of Heat and Chemical Compounds in Fires*, The SFPE Handbook on Fire Protection Engineering, SFPE, Boston, Massachusetts, USA.

Tuovinen H., (1996), CFD *Modelling of Under-Ventilated Fires*, SP REPORT 1996:41, Fire Technology, Swedish National Testing and Research Institute, Borås.

U.S.NRC, (2007), *Verification and Validation of Selected Fire Models for Nuclear Power Plan Applications*: Vol 7, NUREG 1824, United States Nuclear Regulatory Commission, Washington, DC, USA

U.S.NRC, (2007b), *Verification and Validation of Selected Fire Models for Nuclear Power Plan Applications*: Vol 2, NUREG 1824, United States Nuclear Regulatory Commission, Washington, DC, USA

Legislation:
Plan och Bygglag (SFS 1987:10)

Boverkets Byggregler, BBR (BFS 1993:57)

To be published:
Lönnermark A. Björklund A. 2009, *Smoke spread and gas temperatures during fires in retail premises – Experiments and CFD simulations,* SP Technical Research Institute of Sweden, Borås.

Electronic

McGrattan K., (2008c), E-mail correspondens, http://groups.google.com/group/fds-smv/browse_thread/thread/7b00ed076659dfa2/ae1a12b77cf393b6?lnk=gst&q=optimizing+#ae1a12b77cf393b6, 2008-07-22

Personal Comunication

Holmstedt G., Professor, Department of Fire and Safety Engnering and Systems Safety, Lund, 2008

Lönnermark A., SP Technical Research Institue of Sweden, Borås, 2008

Lönnermark A., SP Technical Research Institue of Sweden, Borås, 2008b

Appendix A -Interview sheet for the consultants

The interviews were conducted in Swedish but is here translated. The answers are presented in short versions.

Hi!
My name is Anders Björklund and I am studying at the Lund Technological Institute. I am working on a report that concerns the risks related to the use of CFD-models in fire safety dimensioning with a special focus on the handling of under-ventilated fires.

I want to point out that all information in the interview is anonymous and I will not mention you or your companies name in the report, unless you specifically want to. I therefore ask you to answer as truthfully as you can and not how you wish that it would be.

I also want to point out that I am working part time at a consultancy agency that partly handles fire protection design in buildings. I will not in any way use the information that comes up in the interviews at work, the information stays in the report.

Which CFD-program do you use?
(The question is asked to clarify which program is used)

Mainly FDS: 7

CFX: 1

Why do you use that particular programme?
(The question is asked to get an opinion of their ambition, where FDS for example is free of charge so anyone can download it and create pretty pictures for clients, if you instead have a commercial code that might be an indication of that he company takes CFD modelling serious.)

Mainly easy to use and free of charge (of FDS): 3

Mainly because that what you learned in school: 2

Because it is widely used and there is a lot of knowledge about the program: 2

If a commercial code is used: Do you feel any pressure to sell CFD simulation to cover the license cost?

No it has repaid it self many times: 1 (out of one)

How many are working with CFD in your company?
(The question is asked to get an idea of what their capabilities are to perform quality checks of their own work)

1: 1

2-3: 3

> 3: 4

What level of education do the people working with CFD have?
(The question is asked to get an idea of the competence level)

CFD course: 20 +

Research institute: 2

Internally taught: 2

What kind of education do they have in fire dynamics?
(The question is asked to get an idea of how well they can critically view the CFD output)

Fire Protection Engineer: 23

Other: 2

Describe the working process for a CFD project?
(The question is asked to get a picture of the company's knowledge about CFD, pre work, simplifications, sensitivity analysis, and treatment of output data)

Work in group (2 persons): 3

Work alone: 4

When you perform a simulation, for example an evacuation dimensioning, what critical parameters do you use the CFD output for?

Height to gas layer: 3

Toxicity: 5

Visibility: 6

Temperature: 5

Radiation: 5

When do you use CFD simulations and for what geometries?
(The question is asked to see if the company knows when it is appropriate to use the different output)

Complex geometries (shopping malls): 5

"All geometries": 3

What kind of sensitivity analysis do you usually perform?
(The question is asked to get a picture of which sensitivity analyses that is performed which often can be decisive for several risk sources)

Fire size: 5

Fire location: 2

Yields1

Grid size: 4

Geometry (vent openings): 4

How is the contact with the contractor for the projects that you includes CFD. An example: If the contractor gives a certain budget that you know means that you have to produce material that you are not sure if they are correct, because you are not able to perform the number of sensitivity analysis, will you still deliver the results?
(The question is asked to get an idea of how much the contractor affects the simulation process)

Happens: 2

Never: 6

How much does the costumers demand or need affect the starting point of the modelling. If the client for example want you to show that a certain analytical solution is ok, can it then happen that it will affect the results?
(The question is asked to get a picture if the clients need and will control the simulation process)

Common answer: First an estimation is done whether or not it is possible to verify with CFD.

Common answer: You do want to satisfy the customer.

If your calculation computers are full, can it then happen that you shorten down the simulations?
(The question is asked to get an idea of how much the economy plays a part)

Yes: 1

No: 1

Do you use Pyrosim? Why?
(The question is asked because inexperienced user can come up with many “funny” things when using Pyrosim)

Yes : 3 (because of the geometry)

No: 4

Do you do add anything of your own to the source code and how is this handled?
(The question is asked because with out a through verification it can create a lot of error)

All: No

What kind of computer power do you have for the simulations?
(The question is asked to get an idea of the computer power and through that the simulation possibilities)

Very different but in general the computer cost was seen as low and computer power could easily be bought if the current were insufficient.

Does the company have a person responsible for pure computer support?
(The question is asked to get a picture of the resources of the company)

Yes 2

No: 6

How often is the CFD-program updated?
(The question is asked to se how eager the company is at performing the best possible simulations)

On the FDS mailing list: 2

For every project: 2

Other: 4

Do you have a reference scenario that you run after each upgrade?
(A possible source of error)

All: No

What is your future investment plan in computer power? do you have an investment plan or do for example invest for a new project?

Common answers is that new computer power is bought when needed in a project.

How often do you perform CFD simulations?

Very different levels, from constantly to a few times a year.

Now to more fundamental configurations in the script files of FDS
(they are all asked to get en idea of the companies' knowledge of CFD and FDS)

Which simplifications do you usually perform to save computer power?

Include all standard models: 2

Adiabatic walls: 2

Radiation: 1

What grid resolution do you usually have?

Common answers: 1-2 dm in the near field and 3-4 dm in the far field.

How are the meshes configured?

Overlapping 2

Edge to edge: 3

Non cubic: 1

How is the fire defined in when it comes to heat release rate, soot yield and co production?

How much do you use the default values?

Common answers: when appropriate we use them.

How is the connection to surroundings handled geometrically?

Common answer: enclosure placed in a larger calculation domain.

Are you aware of how FDS handles under-ventilated fires?

Yes: 1

No: 7

Checks the output: 1

How do you deal with under-ventilated fires?

Common answers are that they happen so seldom that it is not worth dealing with.

Appendix B - Interview sheet for the rescue service

Hi!

My name is Anders Björklund and I am studying at the Lund Technological Institute. I am working on a report that concerns the risks related to the use of CFD-models in fire safety dimensioning with a special focus on the handling of under-ventilated fires. In my report I investigate how the rescue service manage their role as a reviewer of analytical dimensioning.

How do you receive analytical dimensionings for referral?

Active (Through cooperation with the local building board): 3

Passive (Just a documentation sent to the rescue service): 7

What are your routines for doing a review of an analytical dimensioning with a CFD/ FDS simulation?

Looking at the input and the discussions: 8

How often do you/have you demanded for a third party check.

Never

What is your background?

Fire Protection Engineer: 9

Other: 1

What is your knowledge about CFD?

The CFD course given at Lund University:: 6

No or little knowledge: 4

What is your knowledge about FDS?

The CFD course given at Lund University: 6

No or little knowledge: 4

Do you know how FDS handle under-ventilated fires?

None

Interviewed rescue services:

- Arvika, Eda och Säffle Räddningstjänstförbund
- Dala Mitt Räddningstjänstförbund
- Enköping- Håbo Räddningstjänst förbund
- Falköping och Tidaholm Räddningstjänstförbund
- Gislaved/Gnosjö Räddningstjänst förbund
- Gästrike Räddningstjänstförbund
- Höglandets Räddningstjänstförbund
- Storgöteborg
- Södertörns brandförsvarsförbund
- Södra Älvsborgs räddningstjänstförbund

Appendix C - Simulation setup – The base scenario

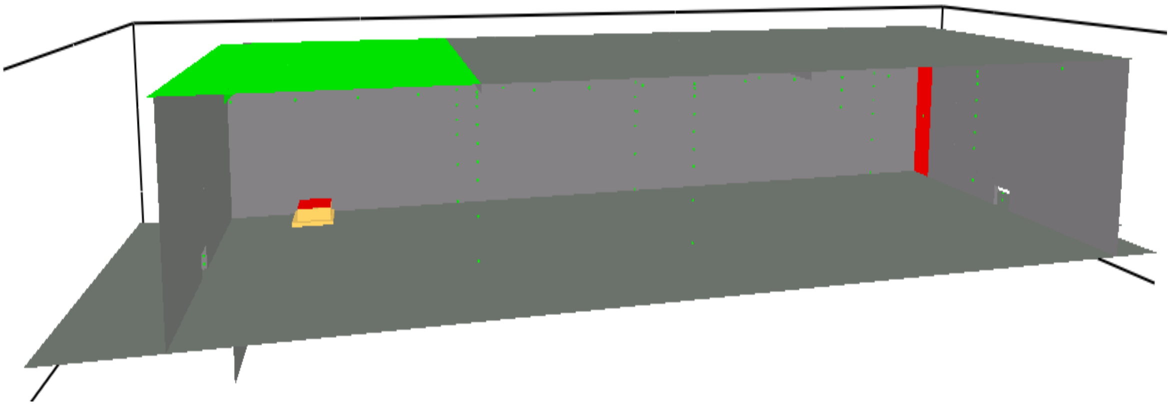


Figure C 1: The geometrical setup, the green s the insulation board, the red in the short wall is the door.

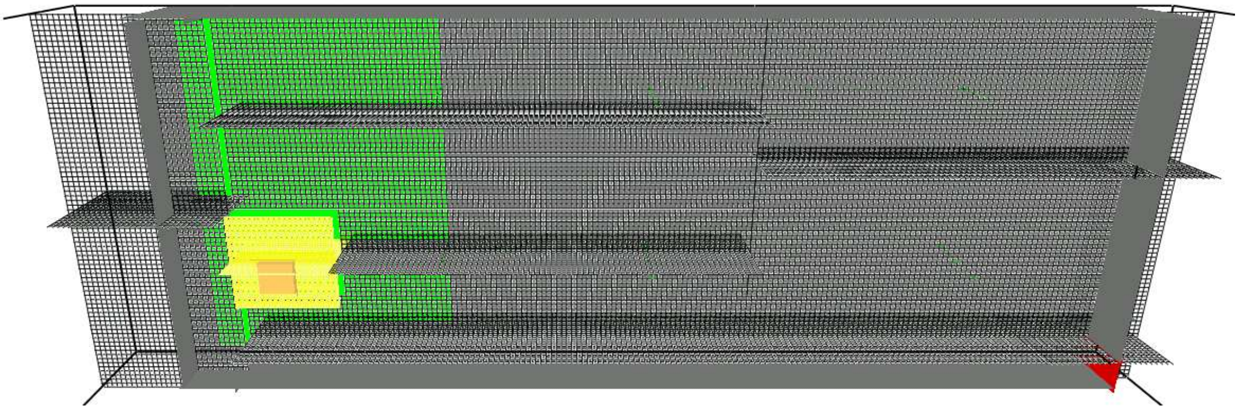


*Figure C 2: The mesh setup seen from below, the horizontal thick lines are the different meshes***.**

Appendix D - Simulation results for Case 7

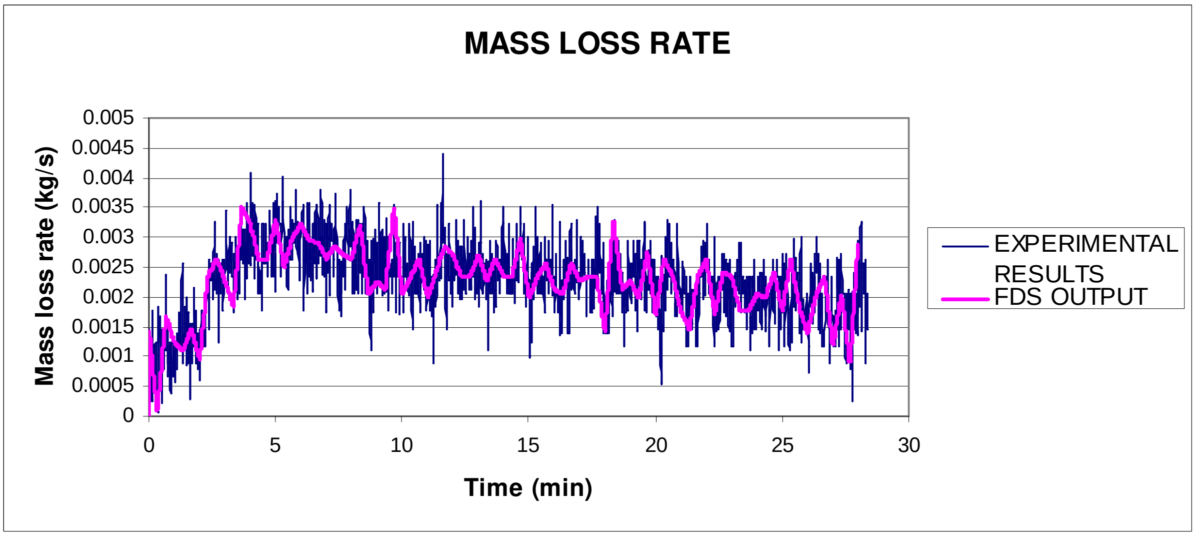


Diagram D 1: Mass loss rate comparison.

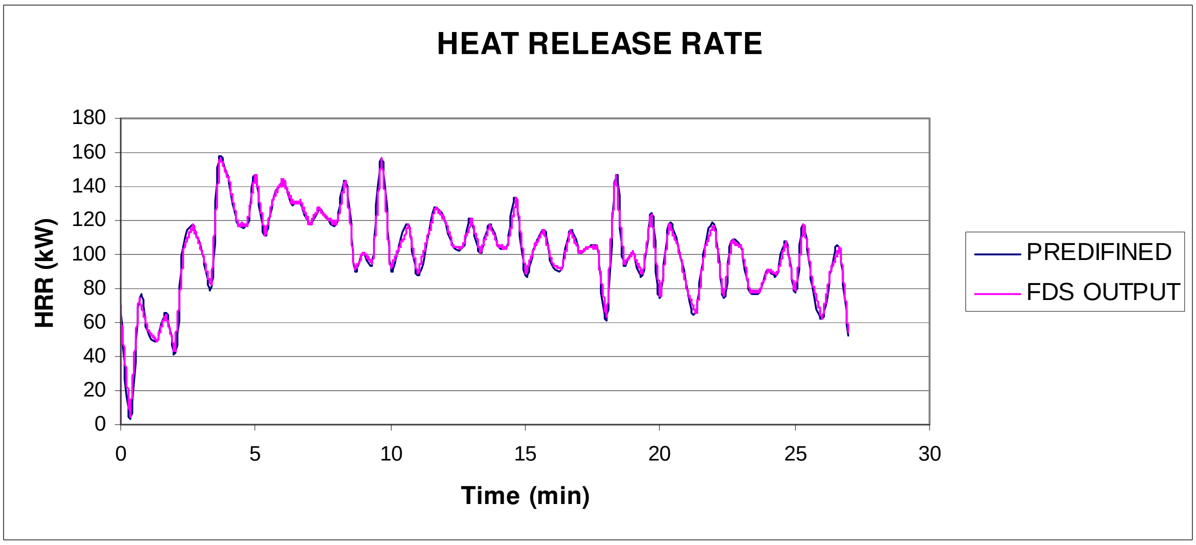


Diagram D 2: Heat release rate comparison.

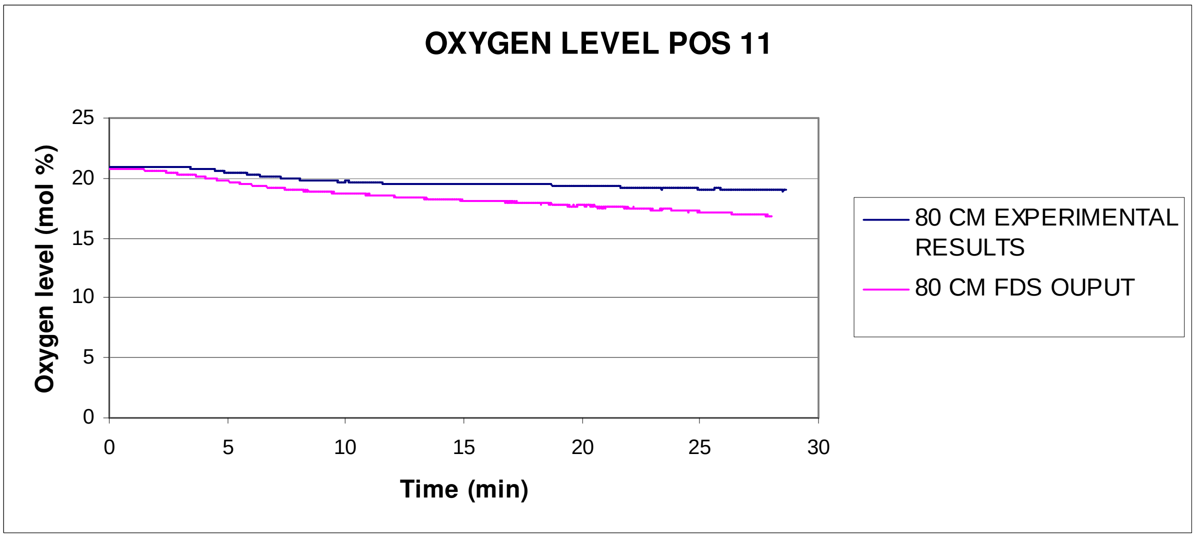


Diagram D 3: Oxygen level comparison.

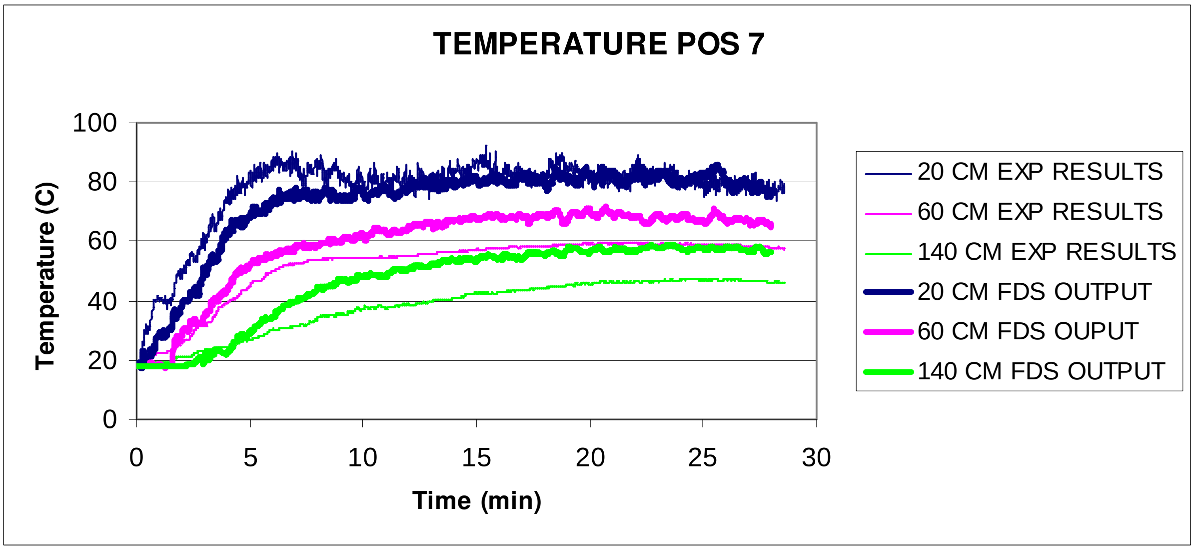


Diagram D 4: Temperature comparison.

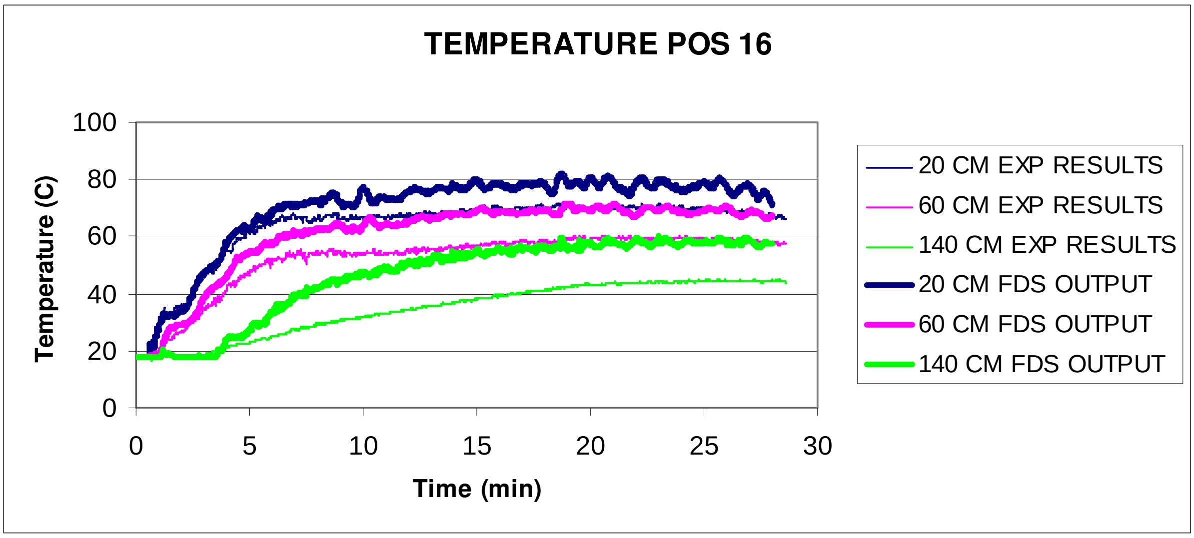


Diagram D 5: Temperature comparison.

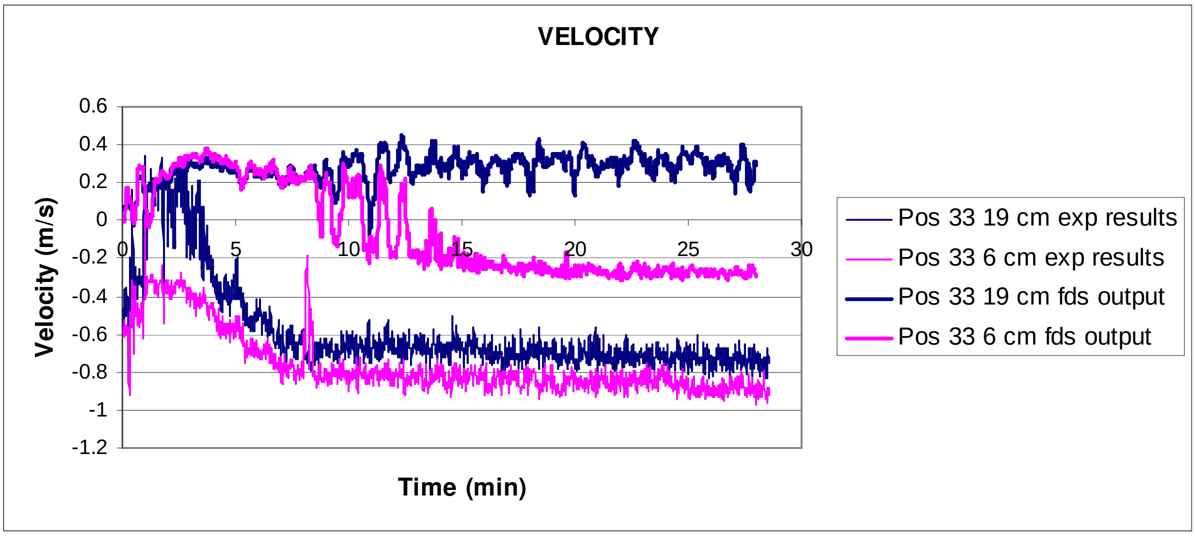


Diagram D 6: Velocity comparison in position 33.

Appendix E - Simulation results for Case 10

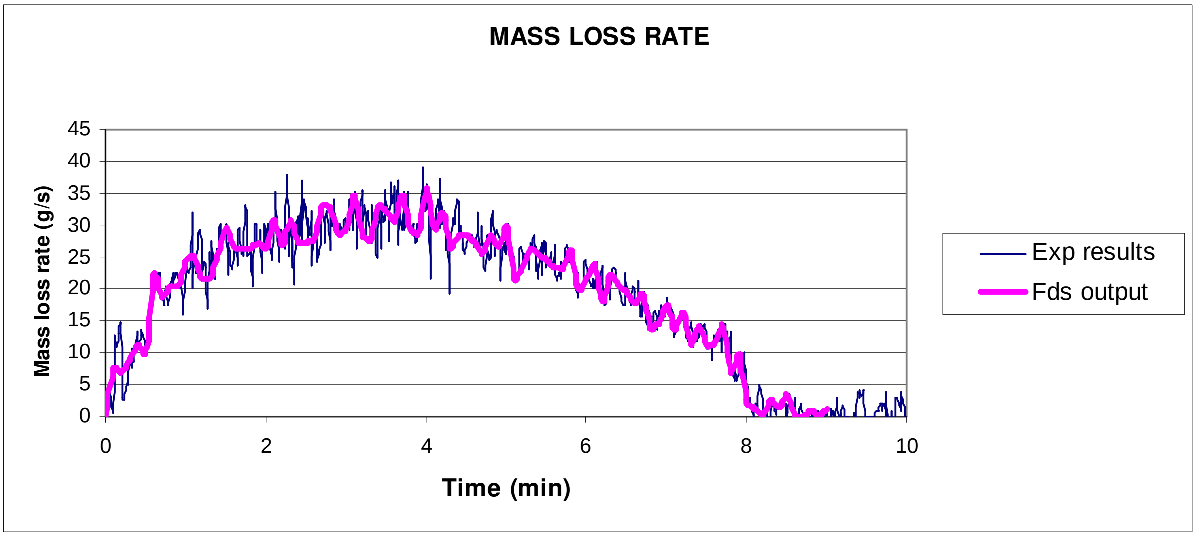


Diagram E 1: Mass loss rate comparison.

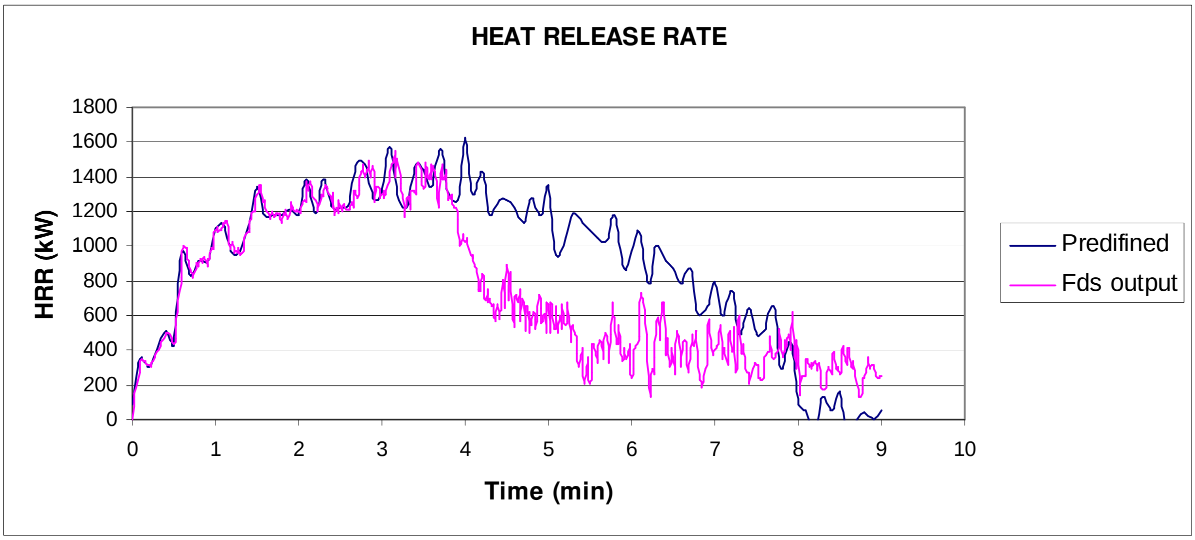


Diagram E 2: Heat release rate comparison.

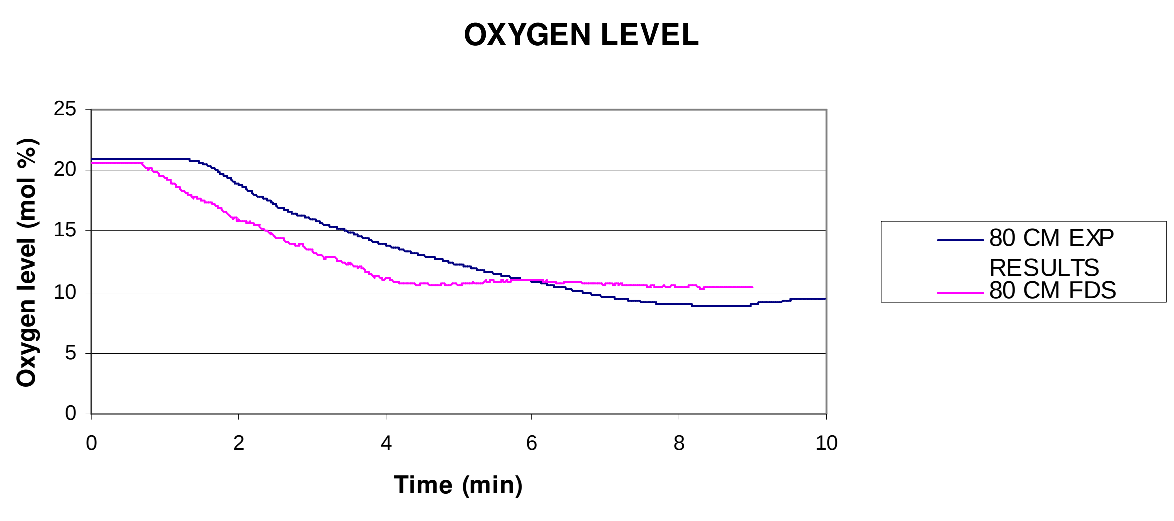


Diagram E 3: Oxygen level comparison.

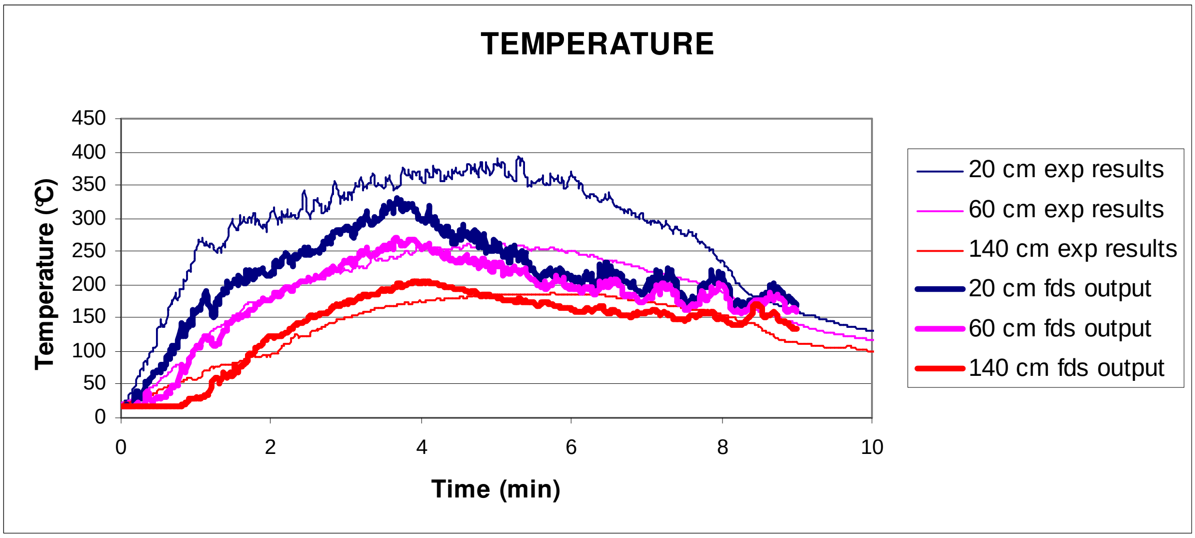


Diagram E 4: Temperature comparison (Pos 7).

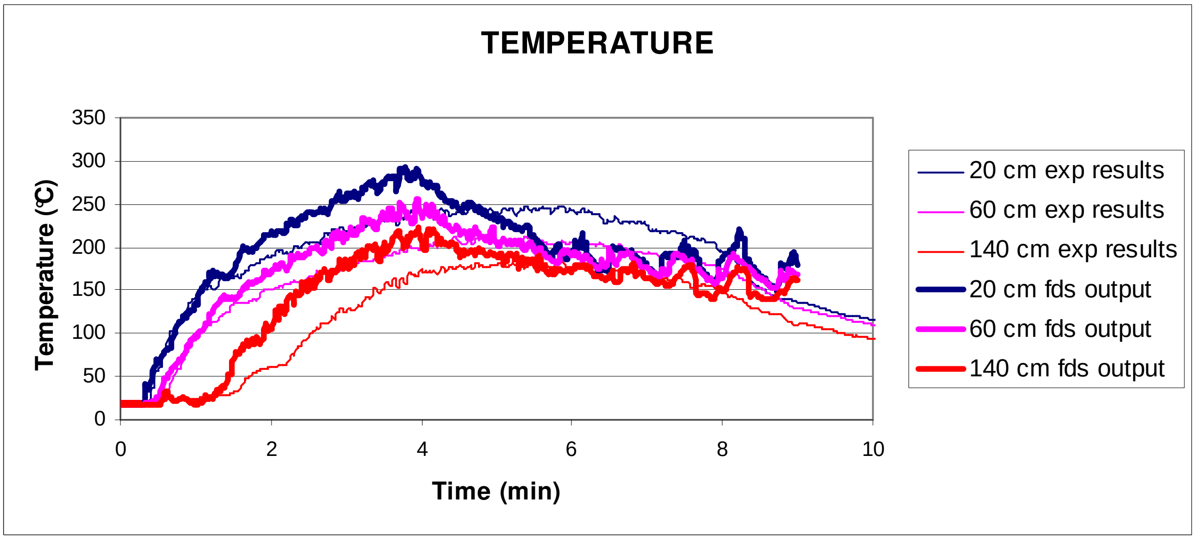


Diagram E 5: Temperature comparison (Pos 16).

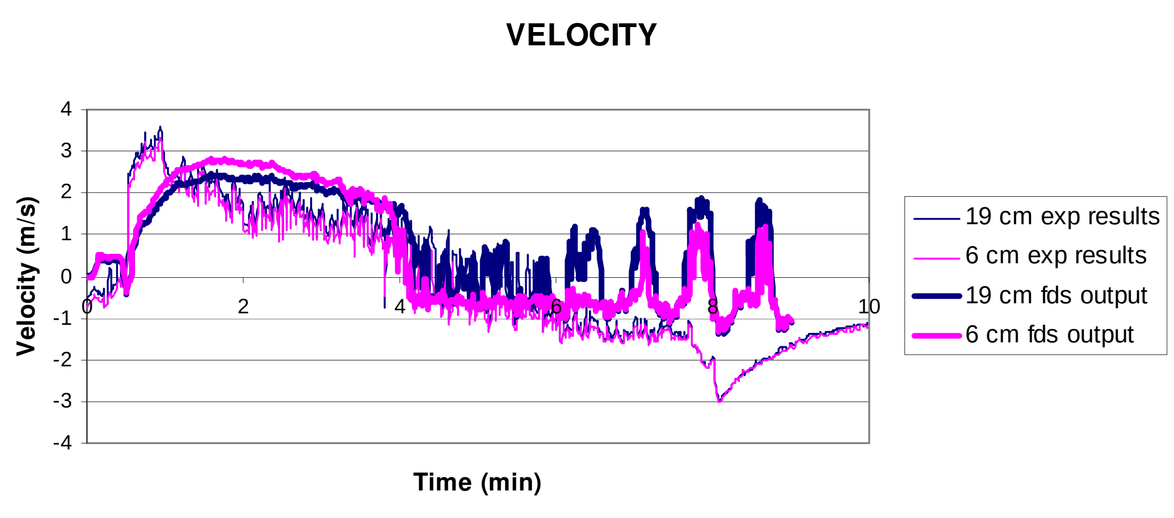


Diagram E 6: Velocity comparison in position 33.

Appendix F - Serial run vs. Base scenario

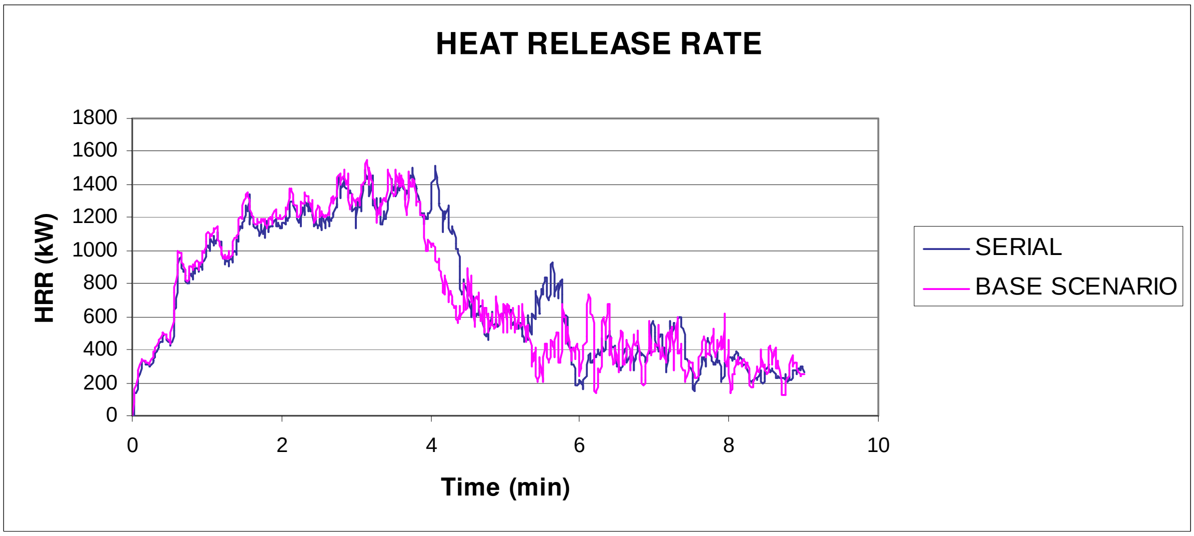


Diagram F 1: Heat release rate for serial and parallel simulation.

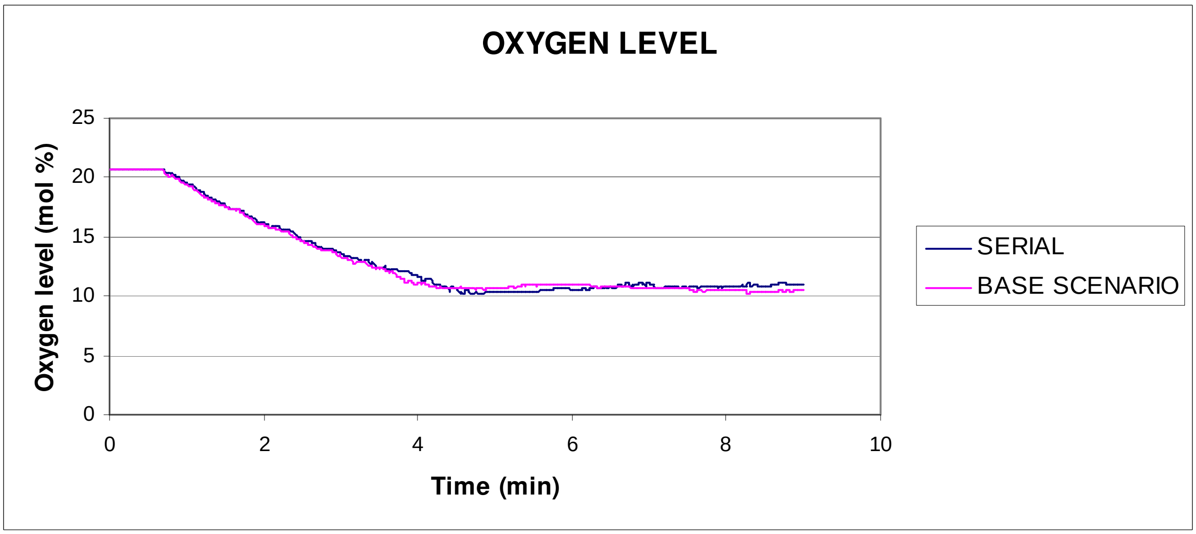


Diagram F 2: Oxygen level for serial and parallel simulation.

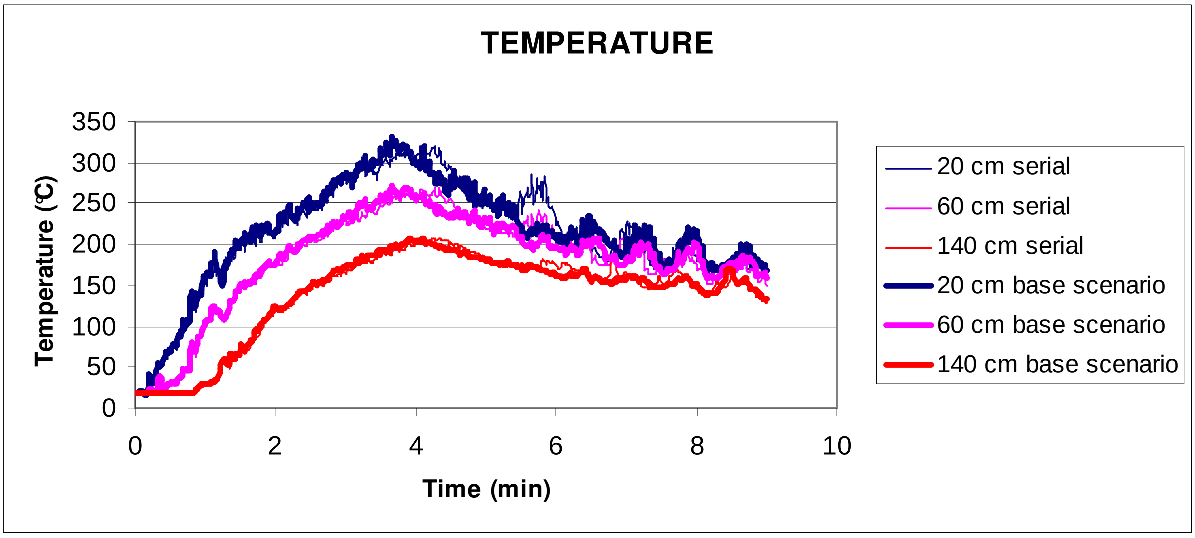


Diagram F 3: Temperature profile for serial and parallel simulation (Pos 7).

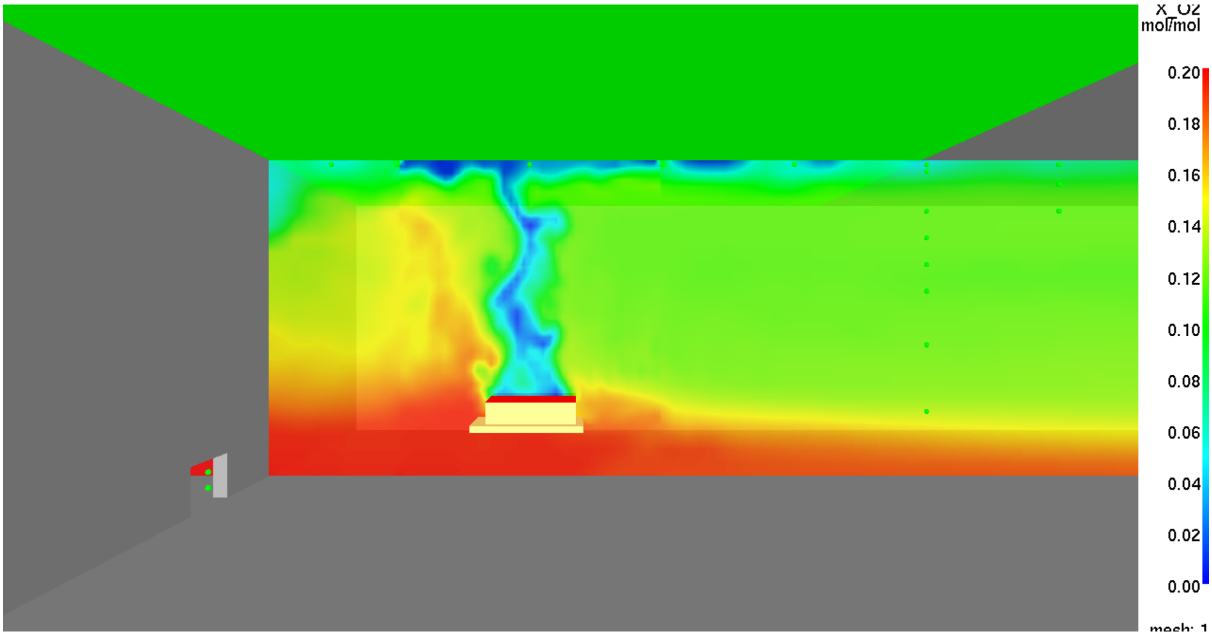


Figure F 1: Slice file for the temperature profile for the serial simulation, through the fire.

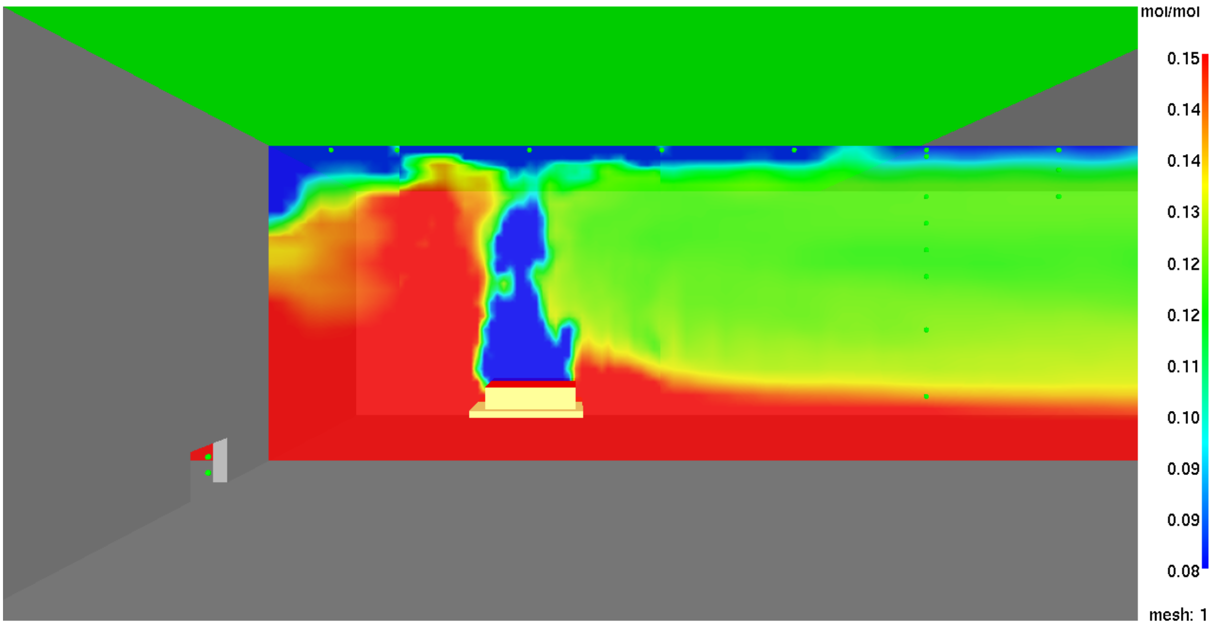


Figure F 2: Slice file for the temperature profile for the base scenario, through the fire.

Appendix G - One fire mesh vs. Base scenario

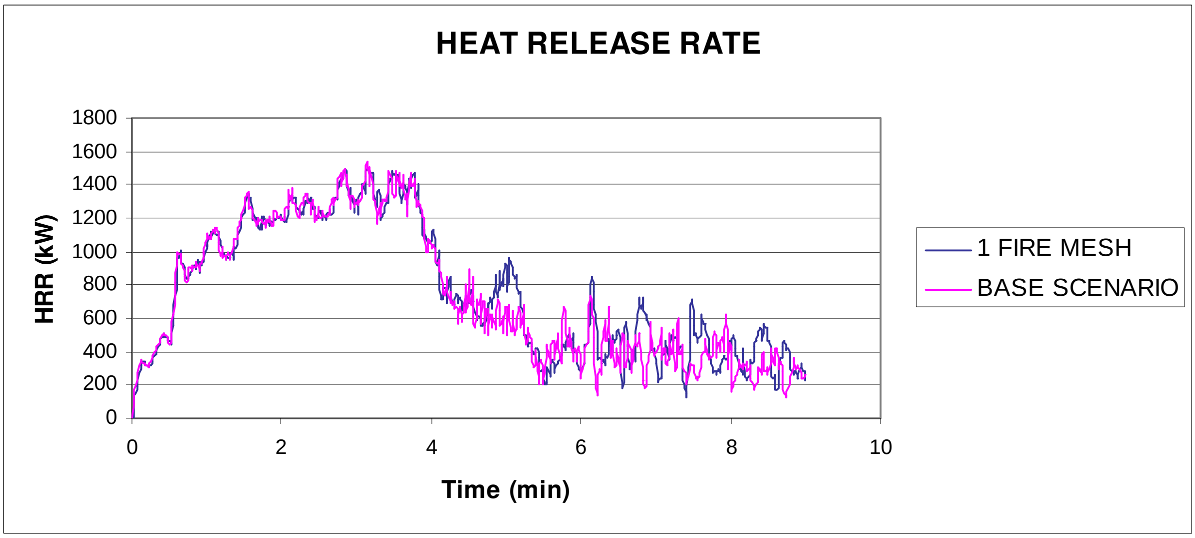


Diagram G 1: Heat release rate for 1 fire mesh vs base scenario.

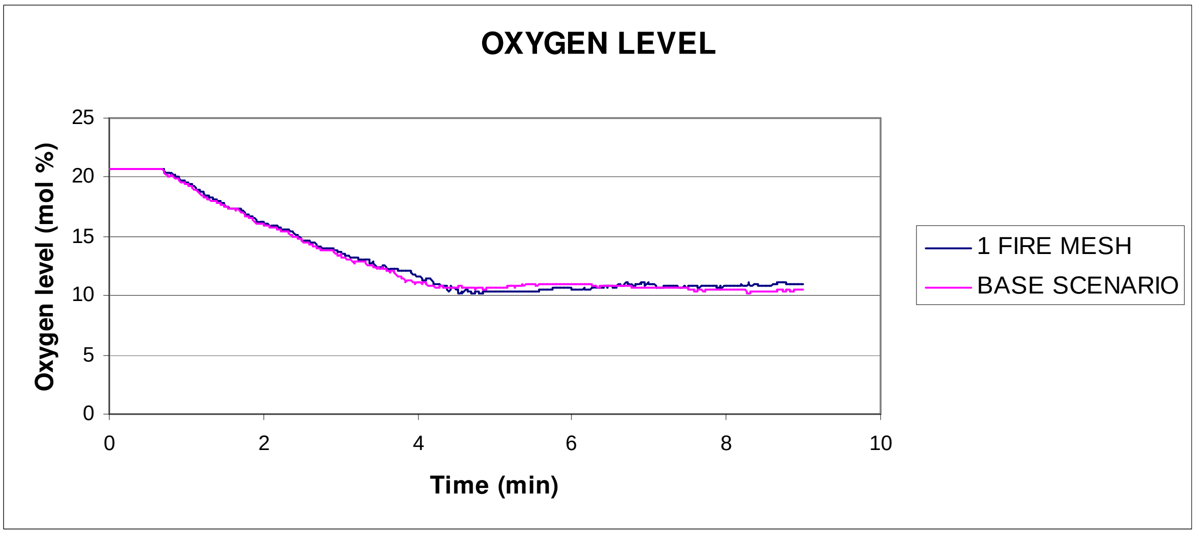


Diagram G 2: Oxygen level for 1 and 1 fire mesh vs base scenario.

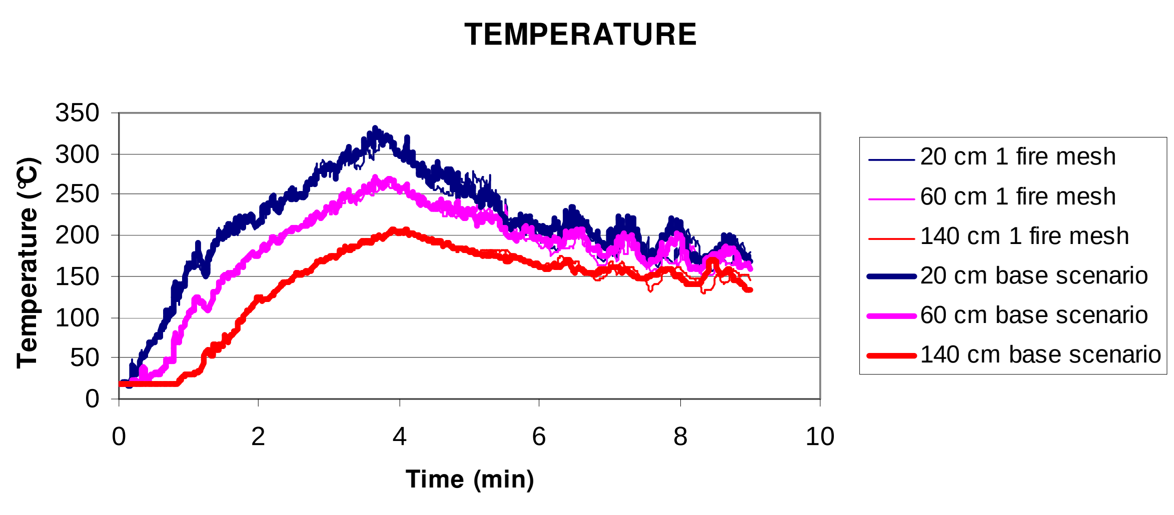


Diagram G 3: Temperature in position 7 for 1 fire mesh vs base scenario.

Appendix H - Small fire mesh vs. Base scenario

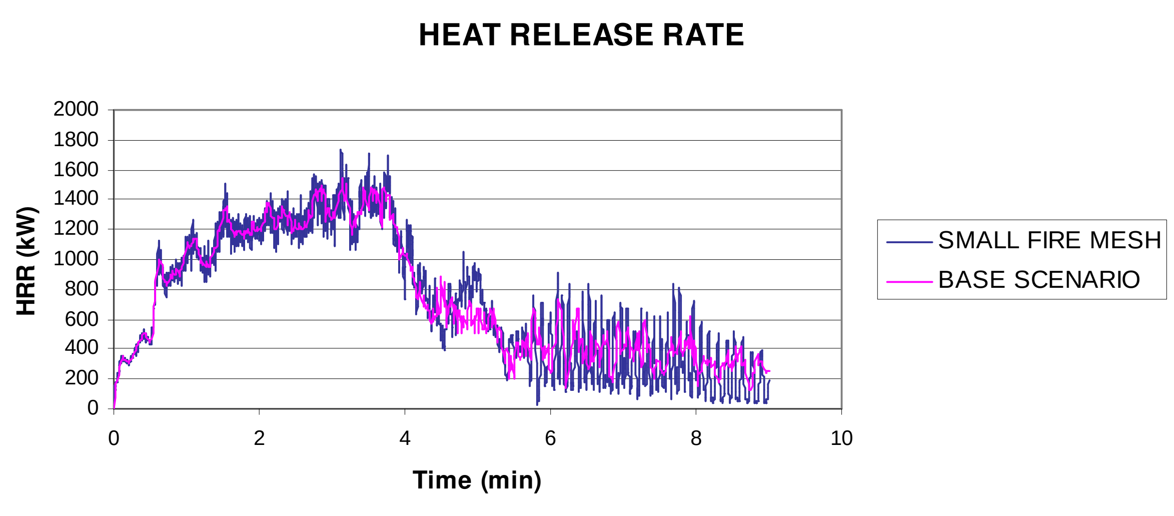


Diagram H 1: Heat release rates for the smaller fire mesh and the base scenario.

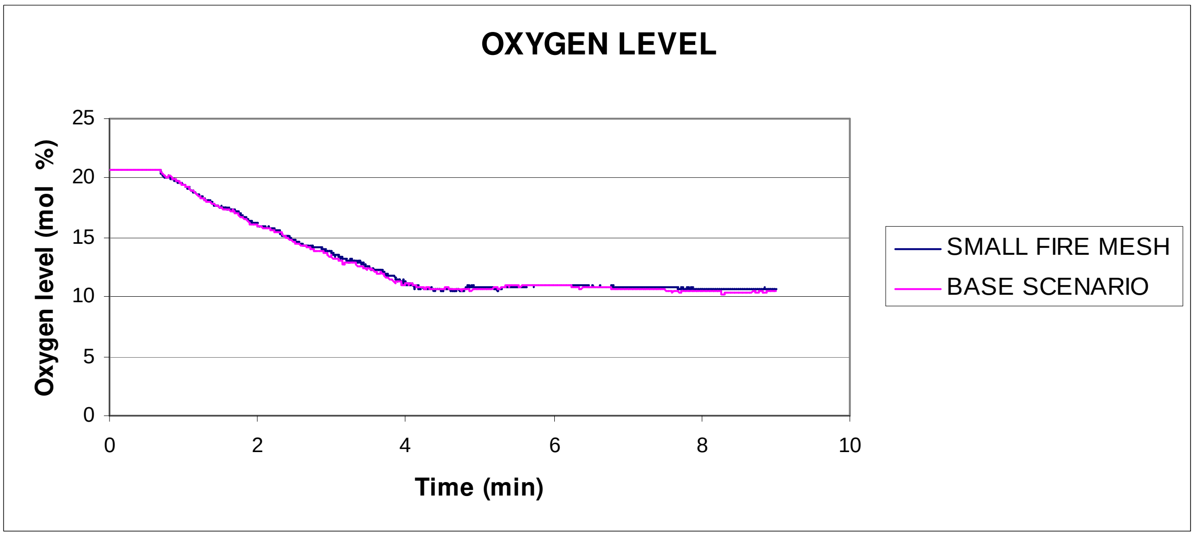


Diagram H 2: Oxygen level for the smaller fire mesh and the base scenario

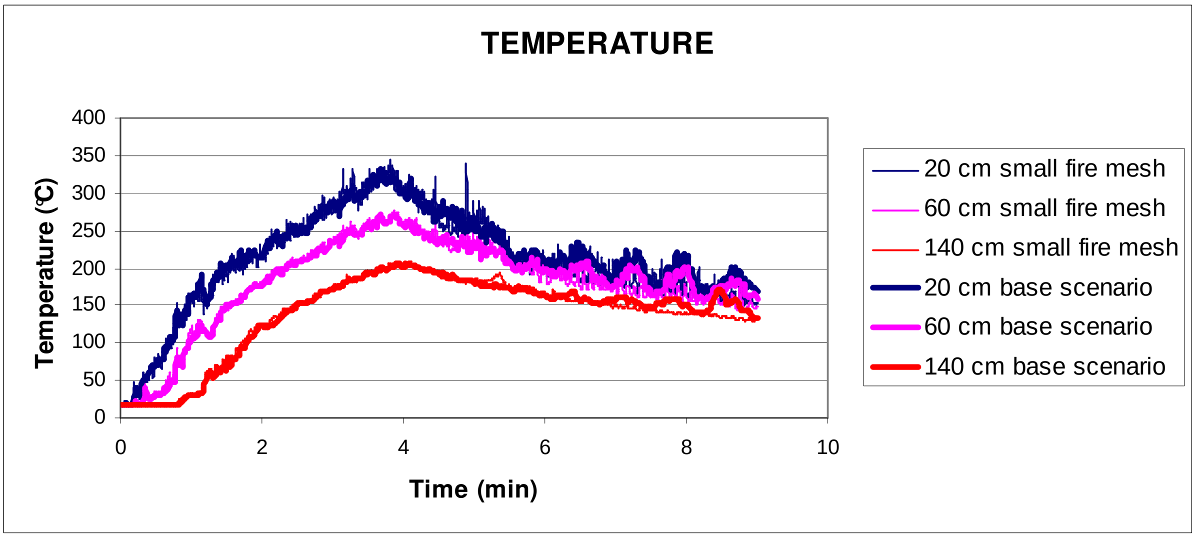


Diagram H 3: Temperature in position 7 for the smaller fire mesh and the base scenario.

Appendix I - Synchronized meshes vs. Base scenario

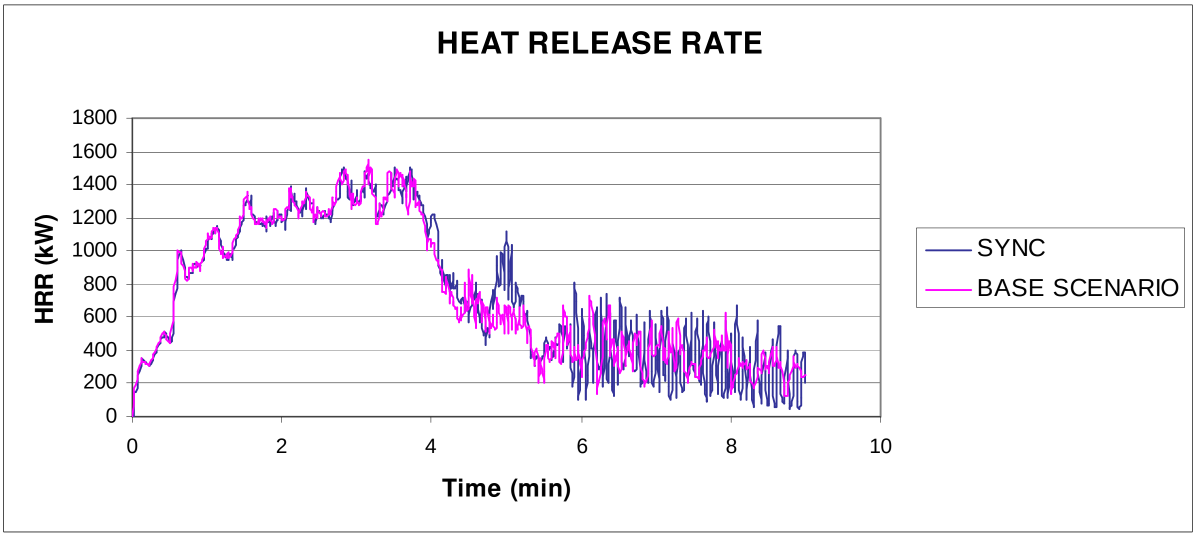


Diagram I 1: Heat release rate for the synchronized and the base scenario.

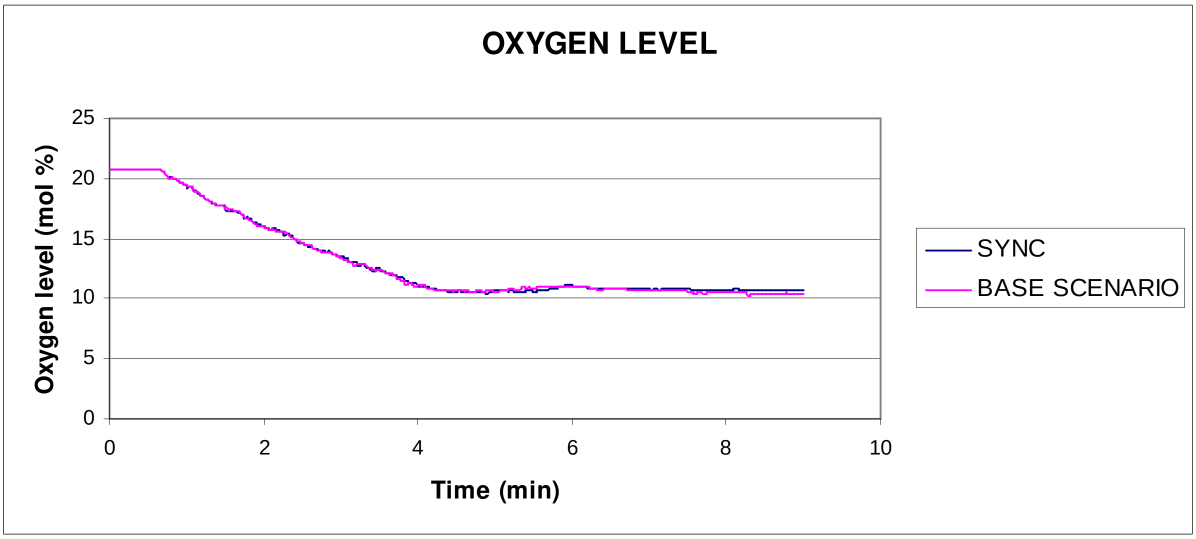


Diagram I 2: Oxygen level for the synchronized and the base scenario.

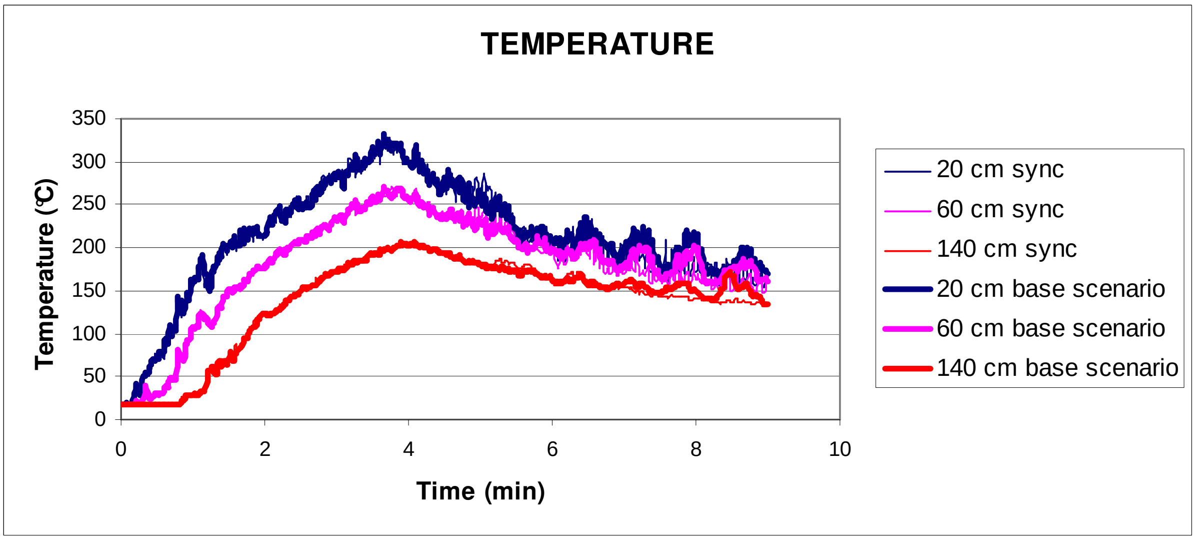


Diagram I 3: Temperature in position 7 for the synchronized and the base scenario.

Appendix J - 8N scenario vs. base scenario

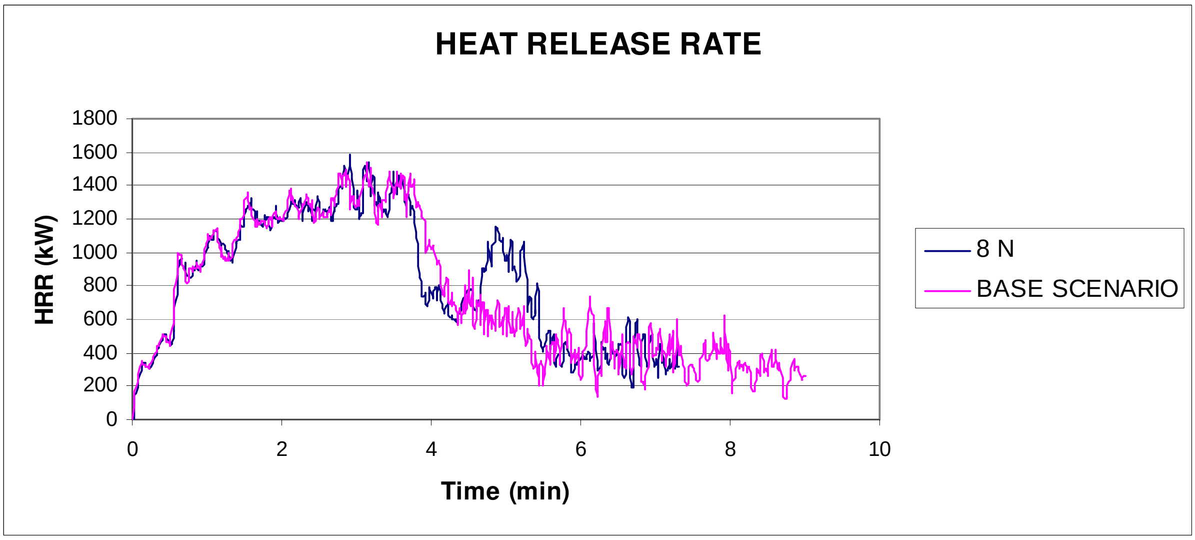


Diagram J 1: Heat release rate for the 8N scenario and the base scenario.

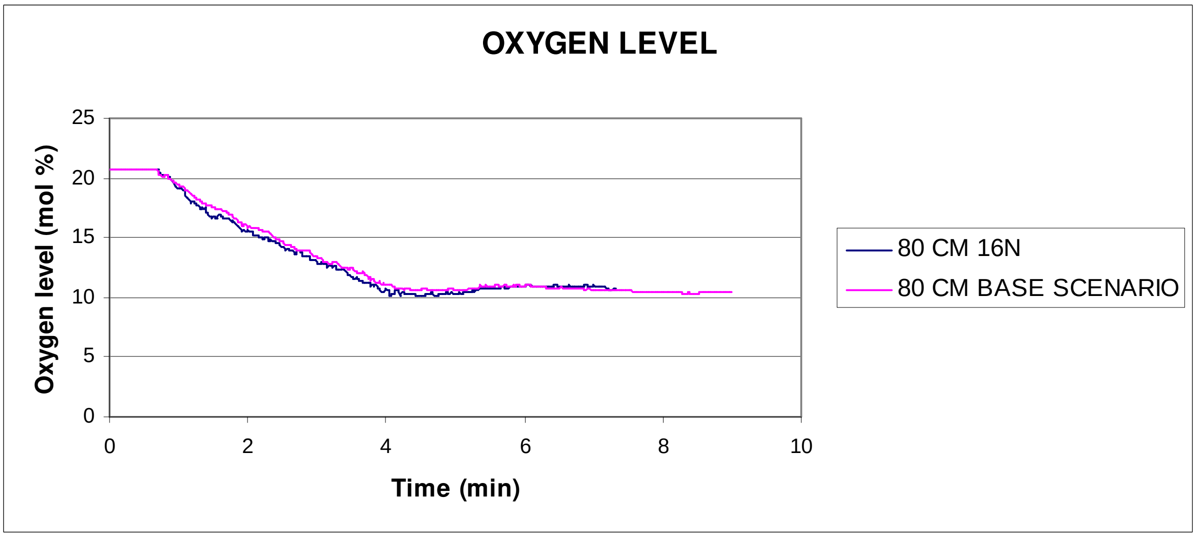


Diagram J 2: Oxygen level for the 8N scenario and the base scenario.

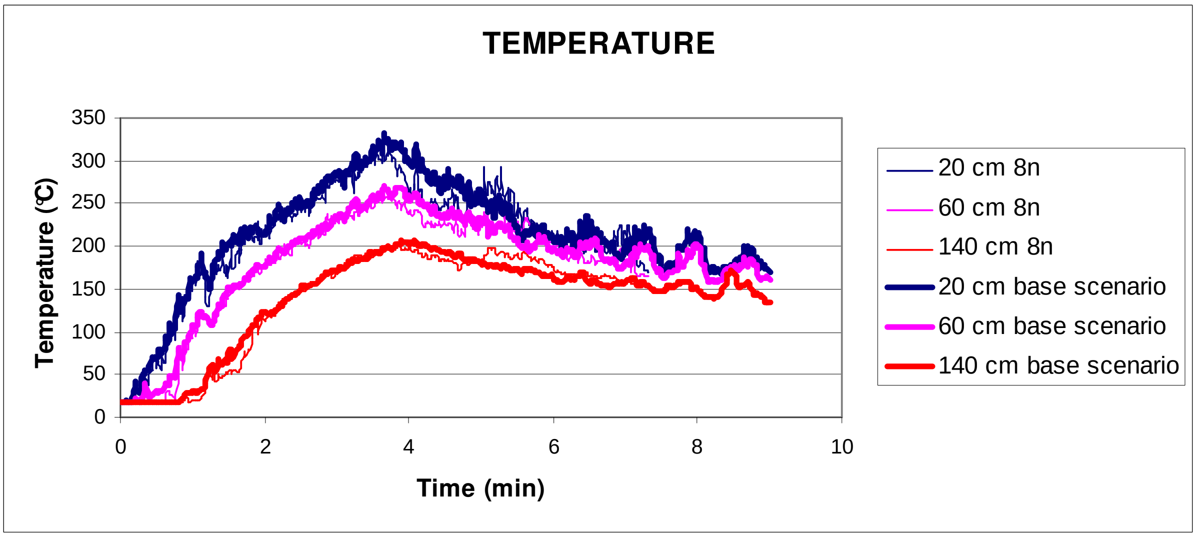


Diagram J 3: Temperature for the 8N scenario and the base scenario.

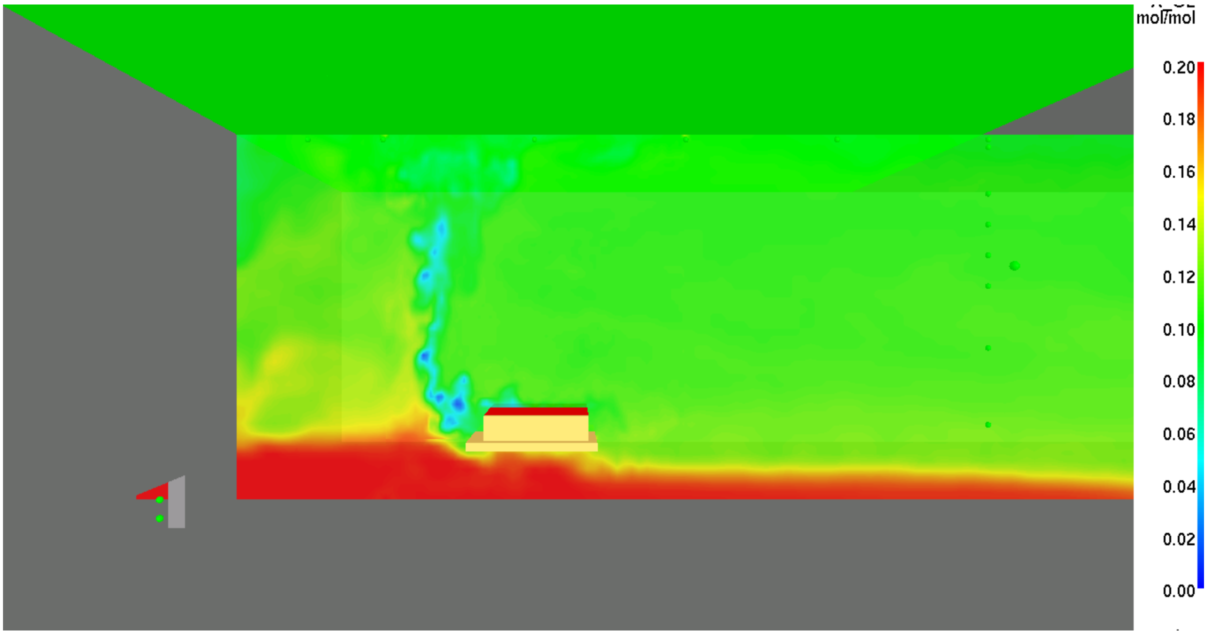


Figure J 1: Slice file for the oxygen level in scenario 8N.

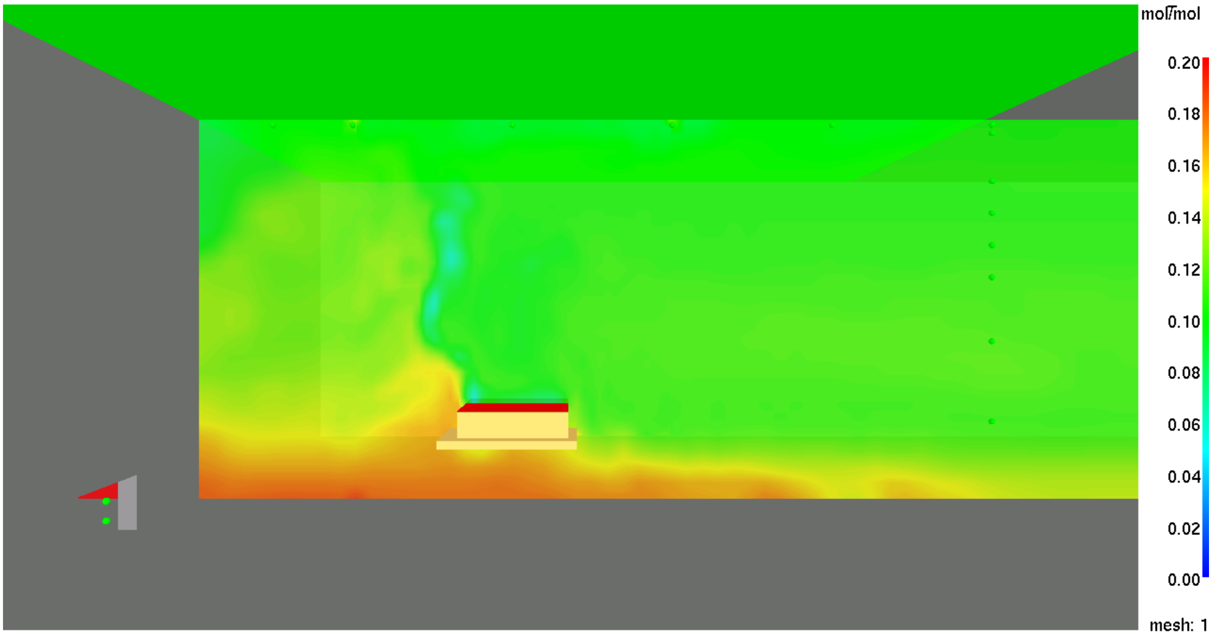


Figure J 2: Slice file for the oxygen level in base scenario.

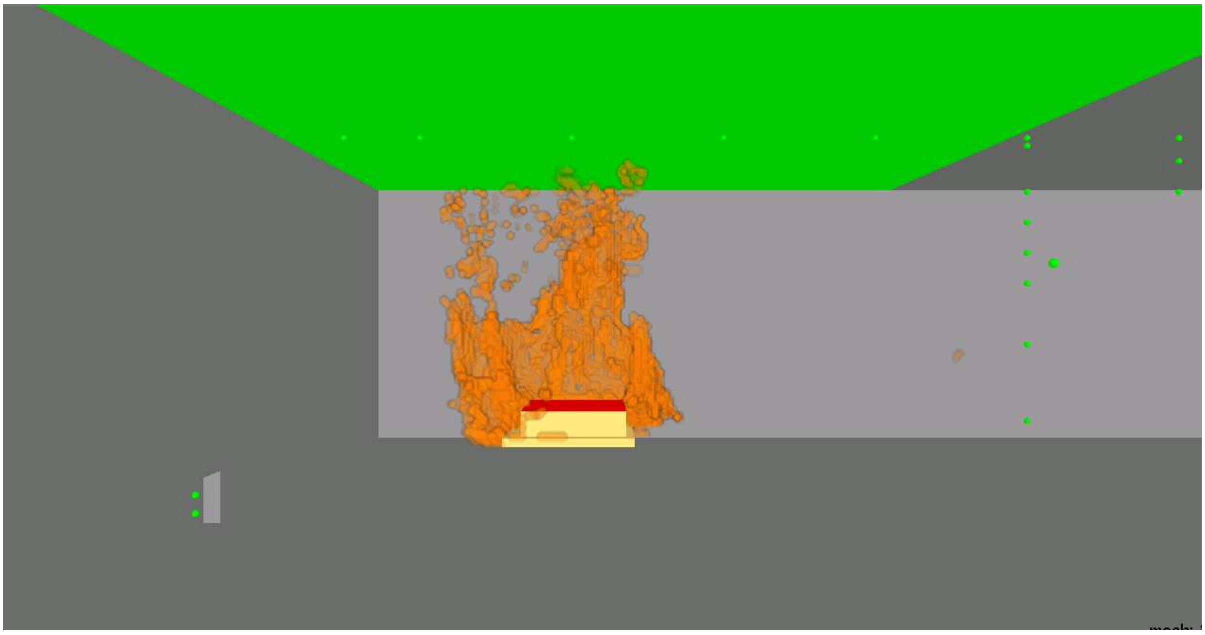


Figure J 3: HRRPUA for all meshes in scenario 8N.

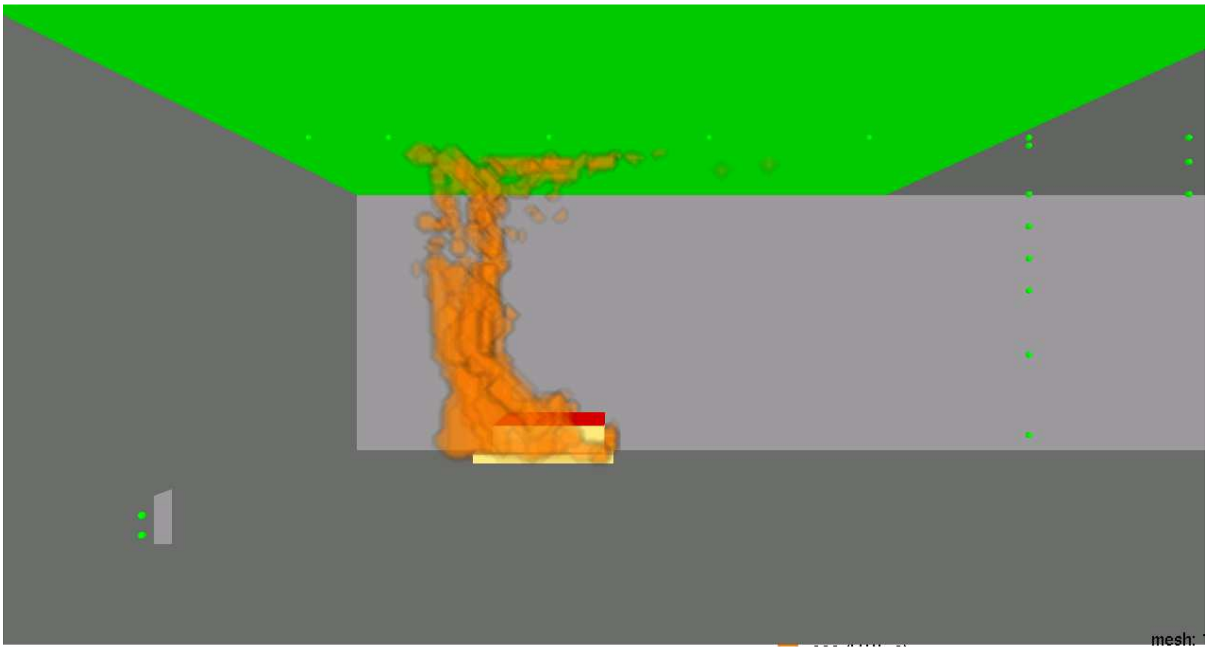


Figure J 4: HRRPUA for all meshes in base scenario.

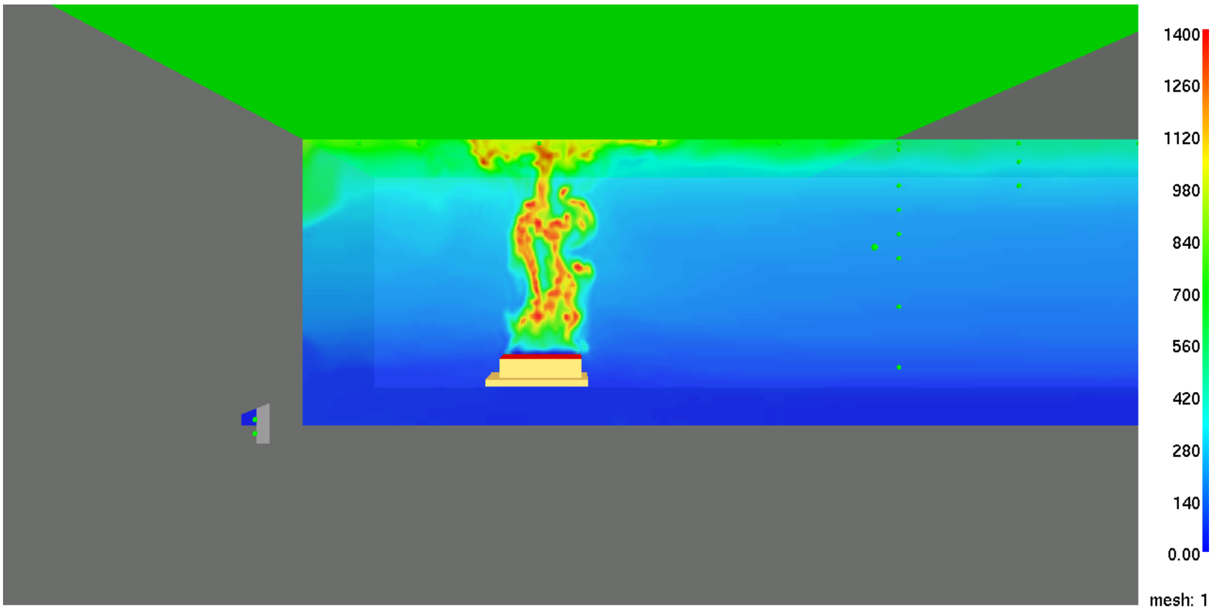


Figure J 5 Temperature in the flame at 3 min in 8n scenario.

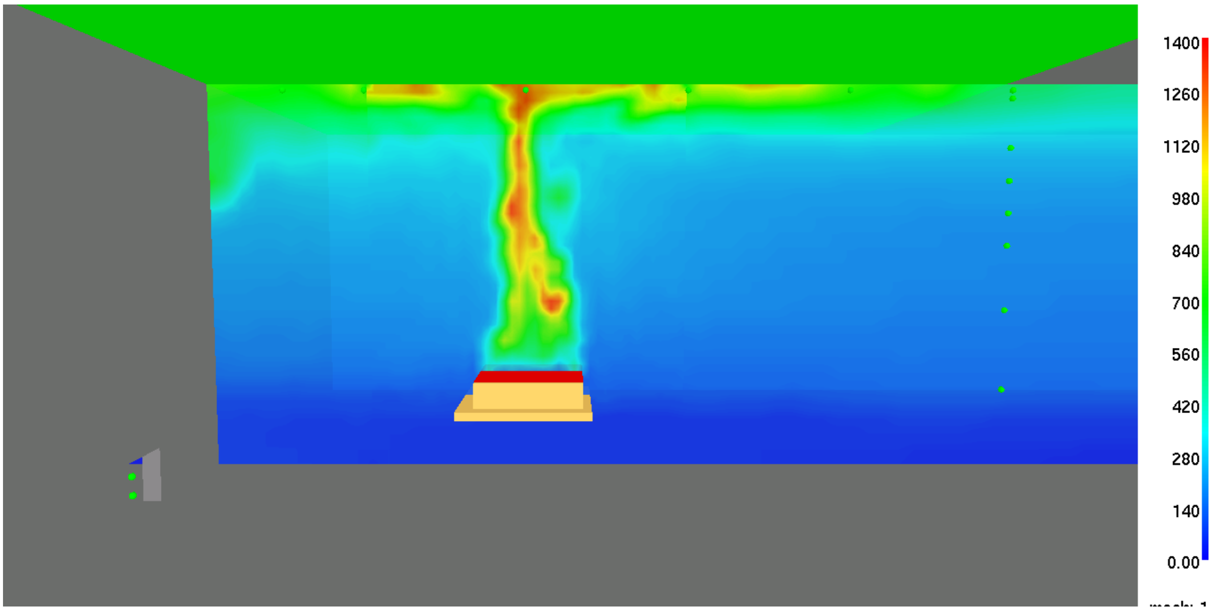


Figure J 6: Temperature of the flame at 3 min in base scenario

Appendix K - 0.7 x Mass loss rate compared to test 10

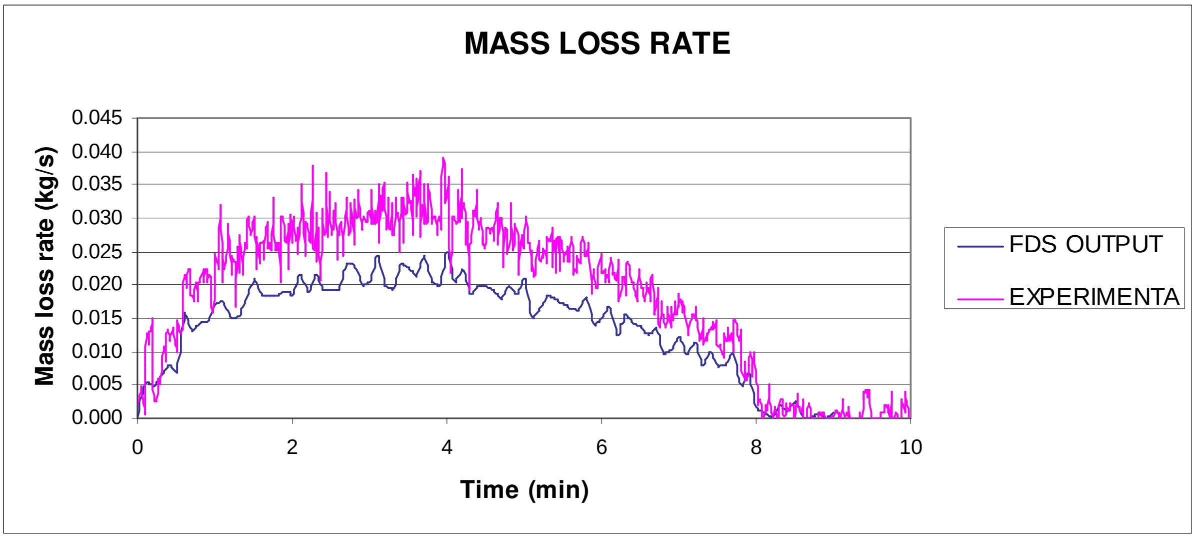


Diagram K 1: Mass loss rate comparison.

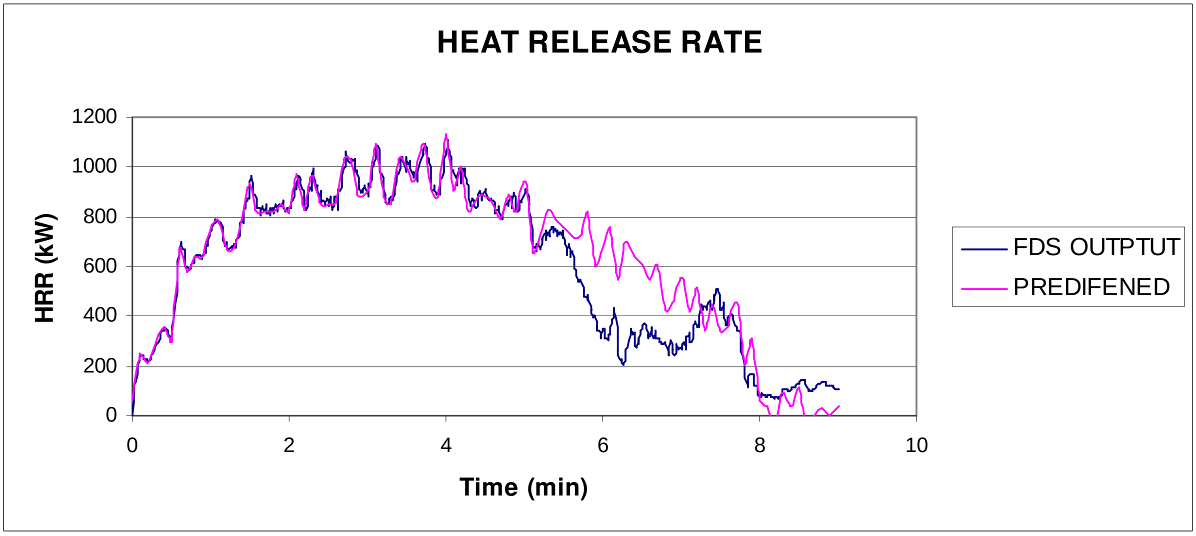


Diagram K 2: Heat release rate comparison.

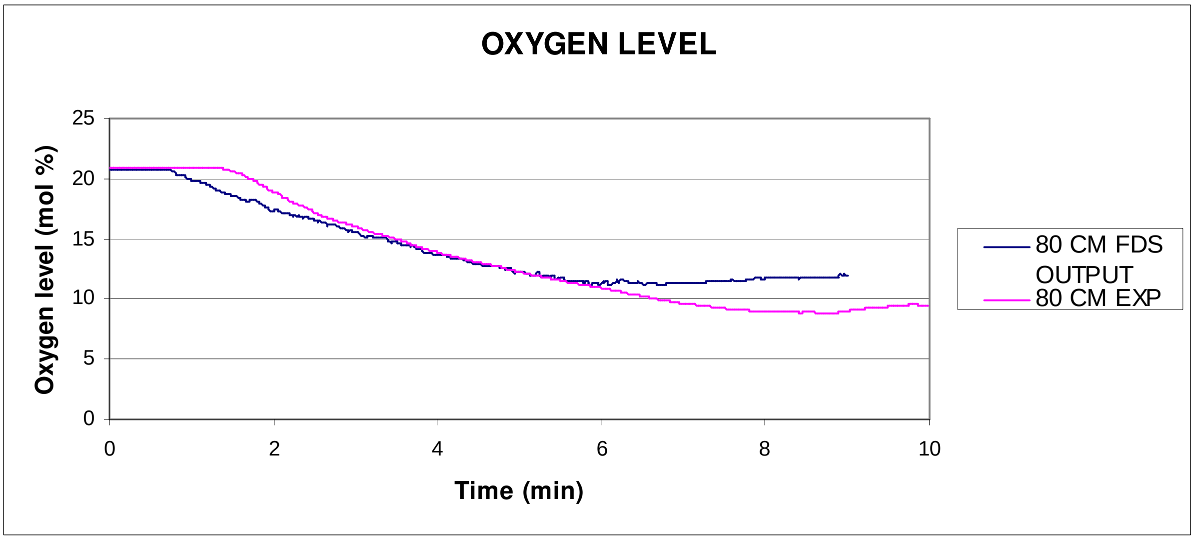


Diagram K 3: Oxygen level comparison.

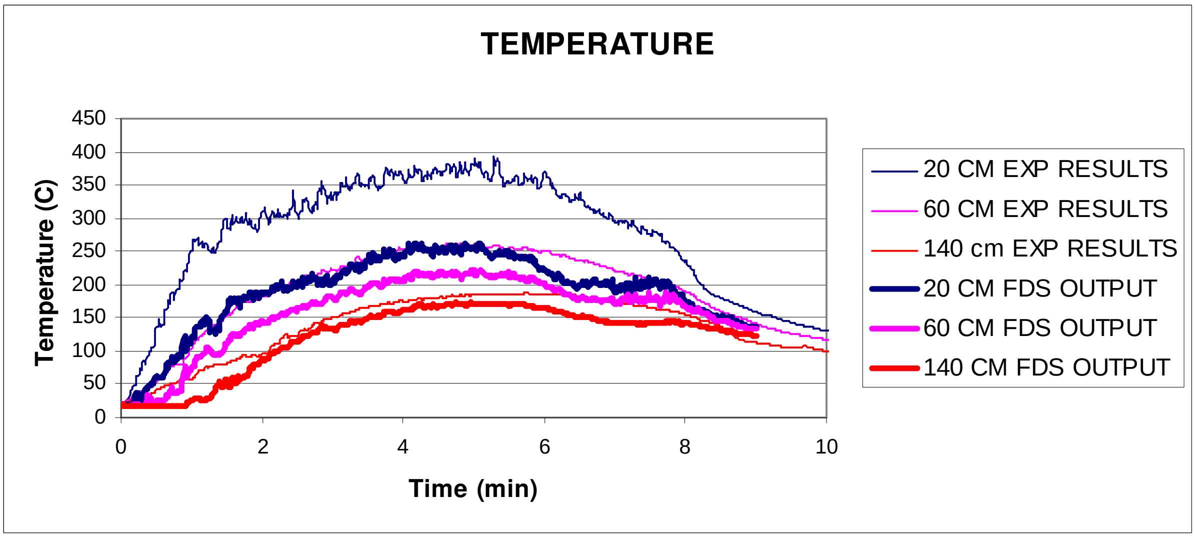


Diagram K 4: Temperature comparison (Pos 7).

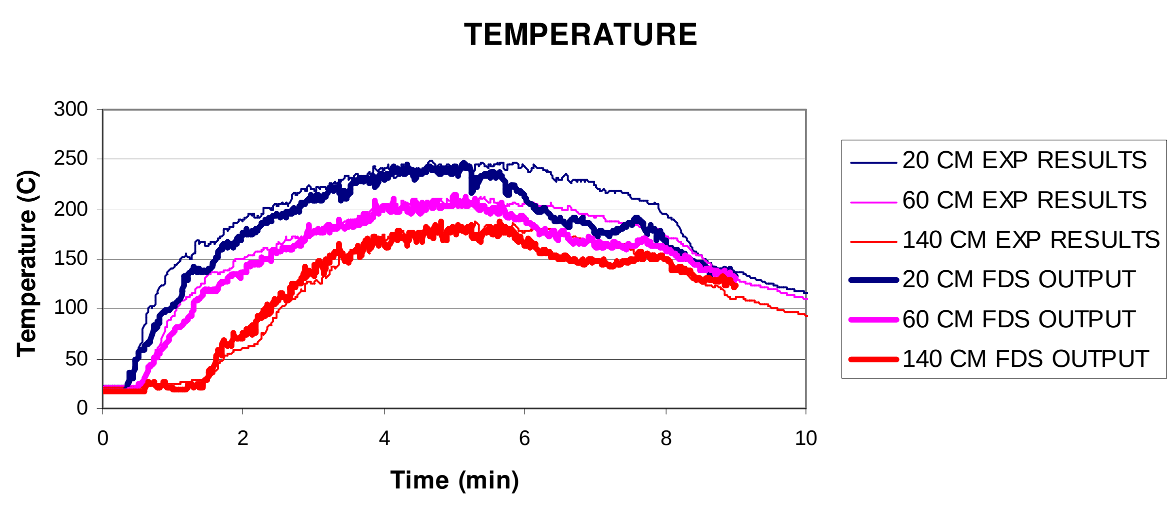


Diagram K 5: Temperature comparison (Pos 16)

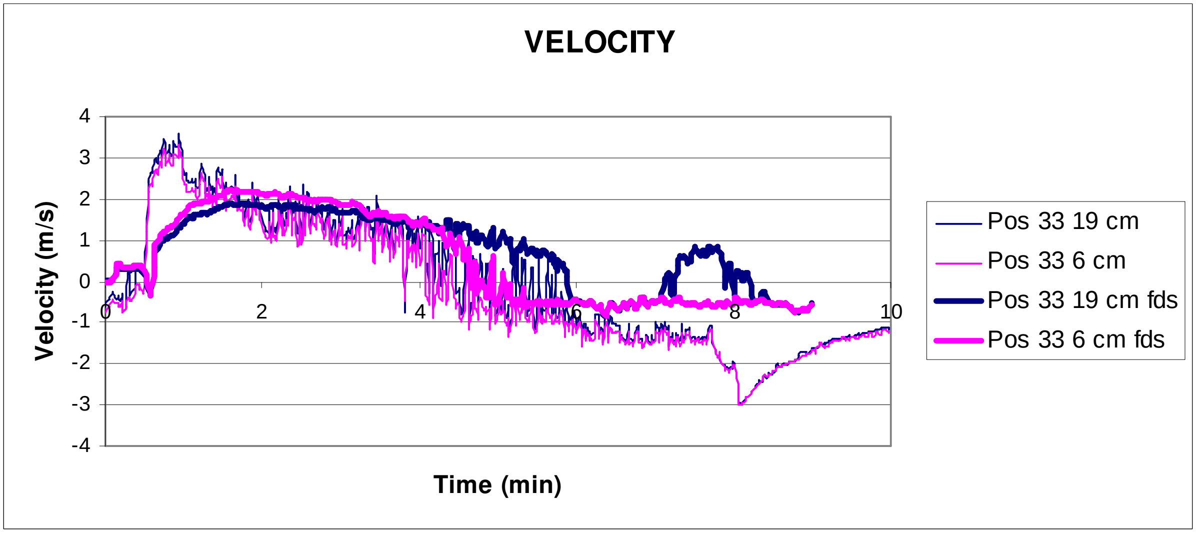


Diagram K 6: Velocity comparison

Appendix L - Experimental Results - Test 1

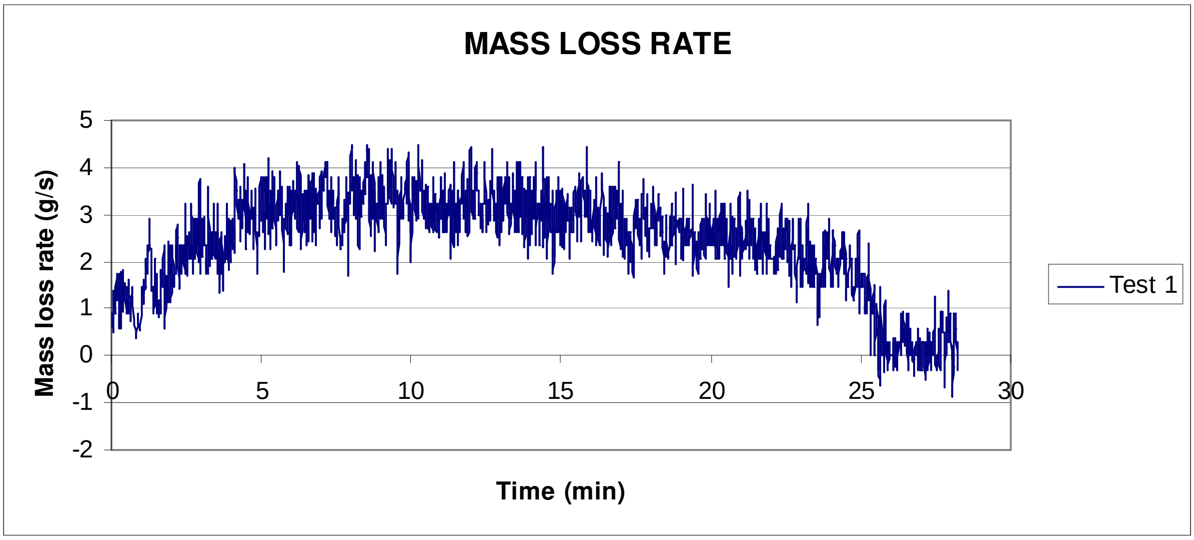


Diagram L 1: Mass loss rate.

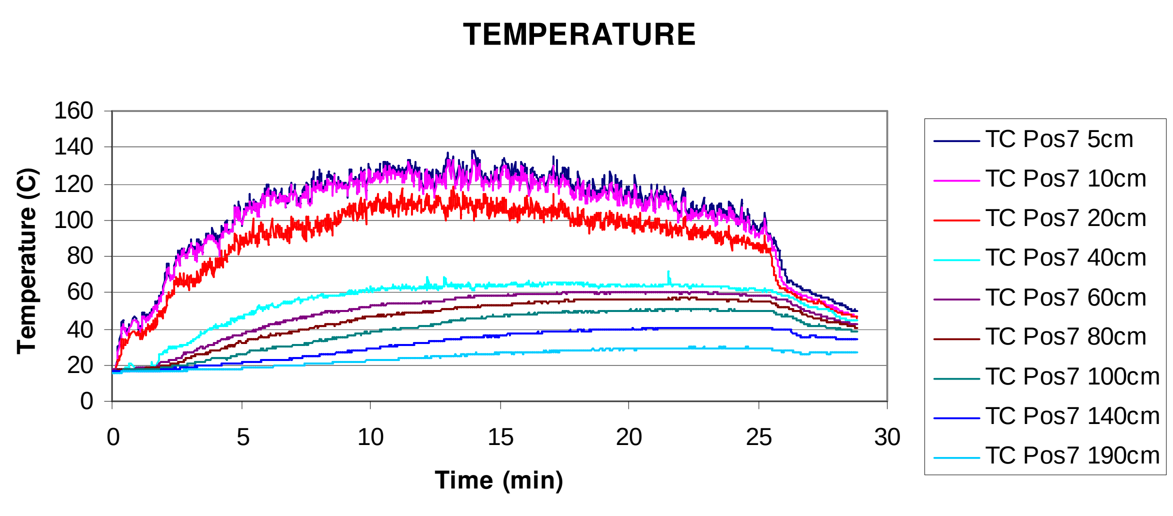


Diagram L 2: Temperature profiles

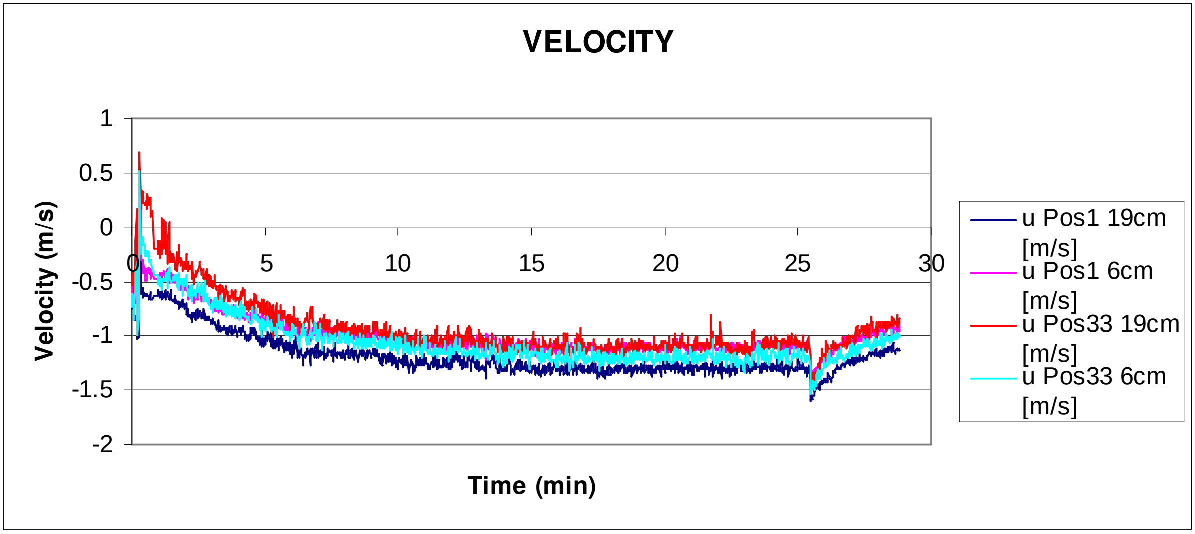


Diagram L 3: Velocity profiles

Appendix M - Experimental Results - Test 2

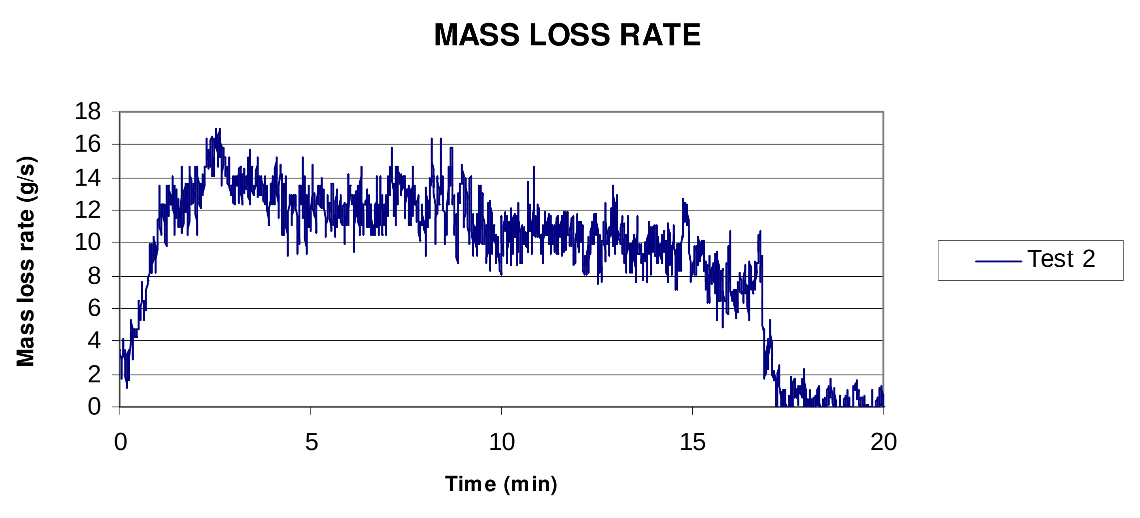


Diagram M 1: Mass loss rate

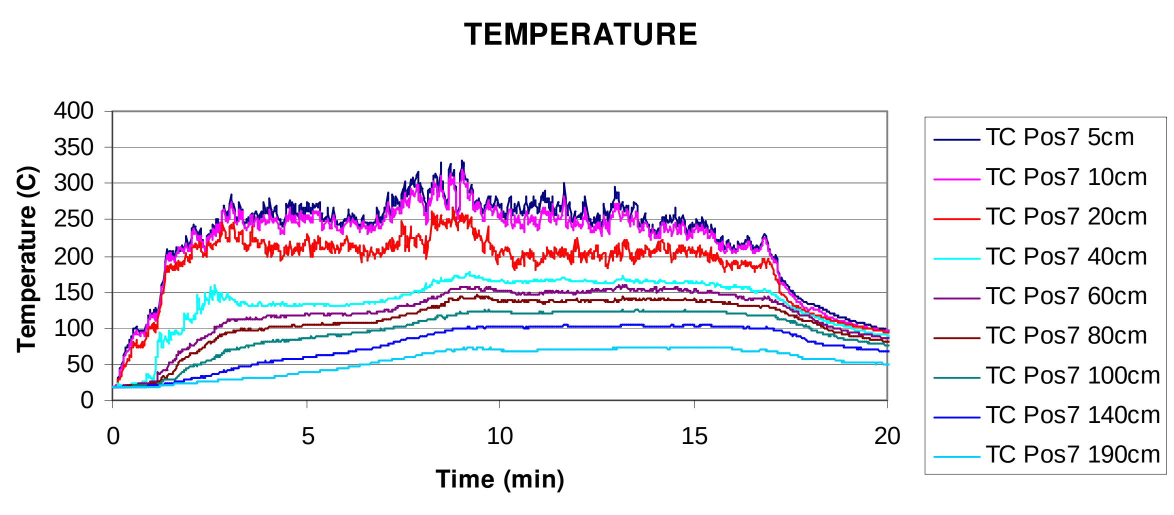


Diagram M 2: Temperature profiles

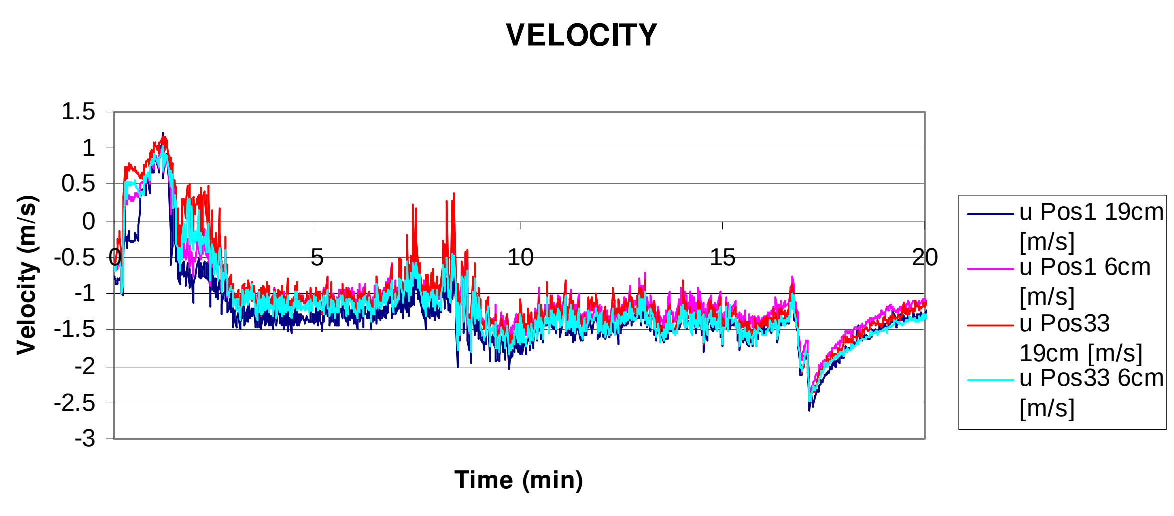


Diagram M 3: Velocity profiles

Appendix N - Experimental Results - Test 3

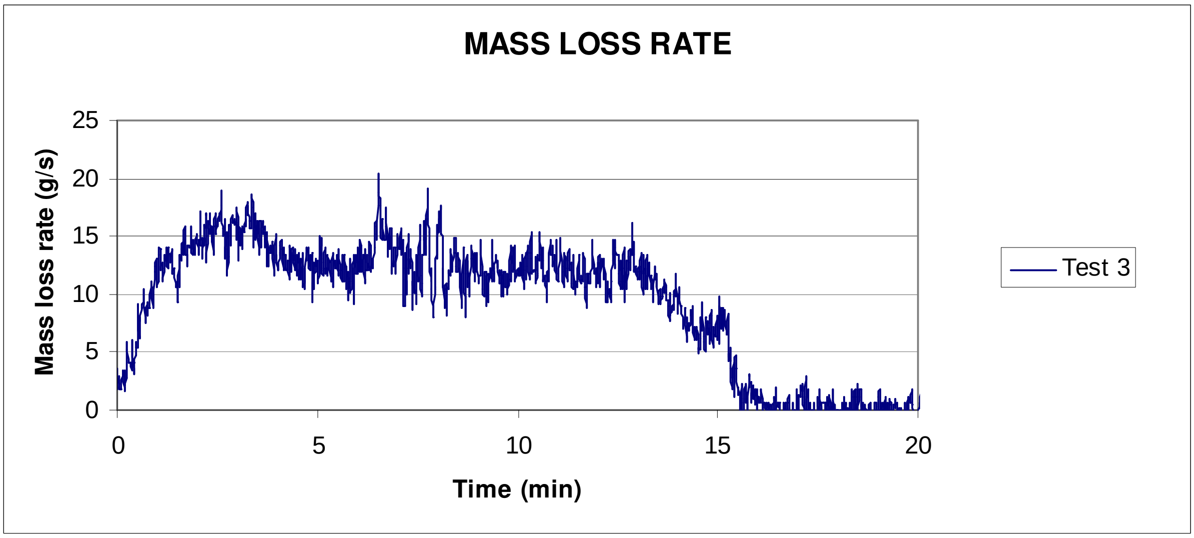


Diagram N 1: Mass loss rate.

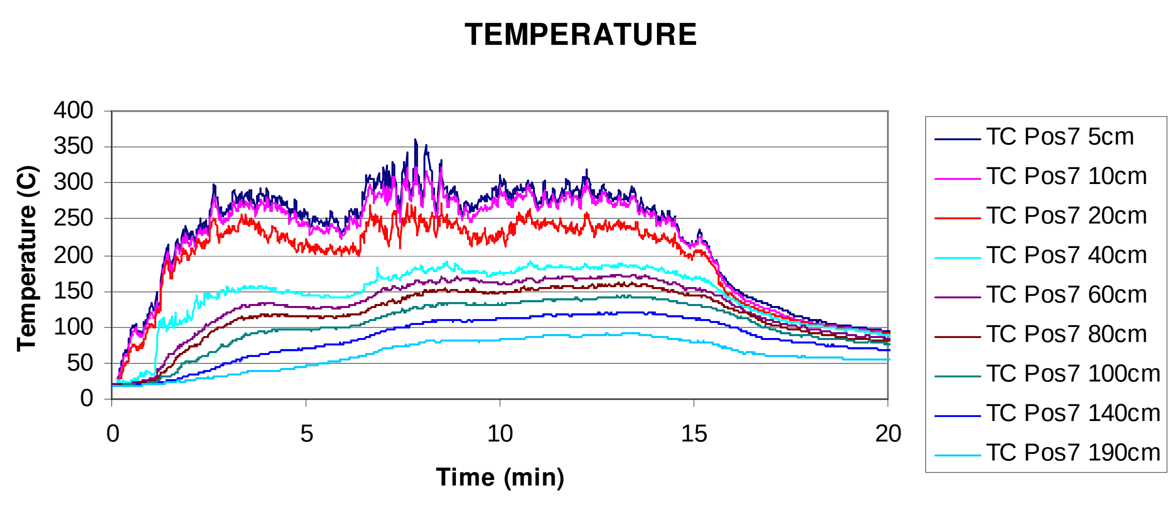


Diagram N 2: Temperature profiles

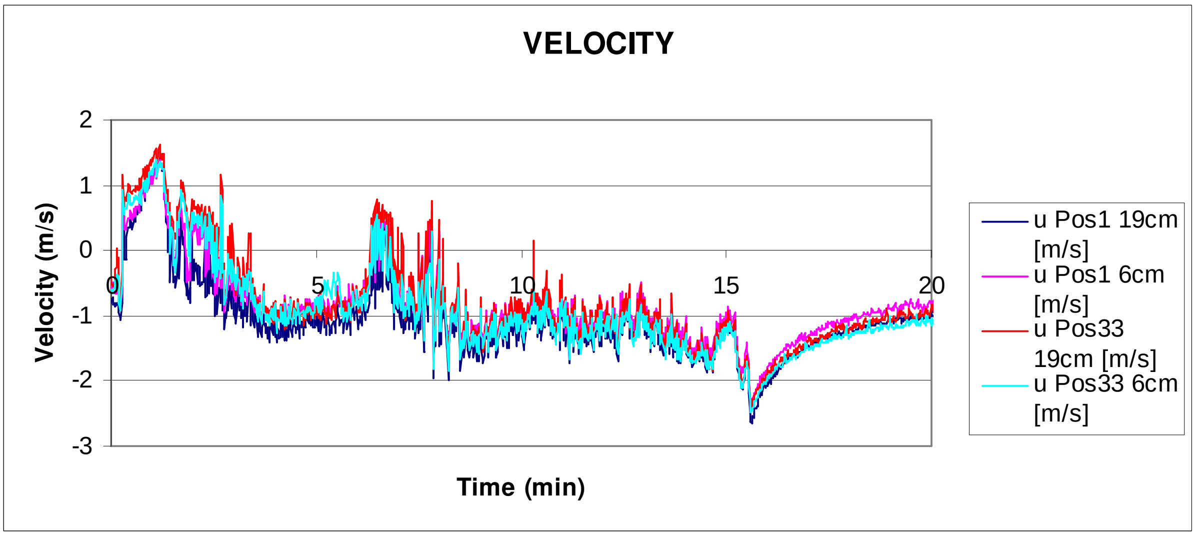


Diagram N 3: Velocity profiles

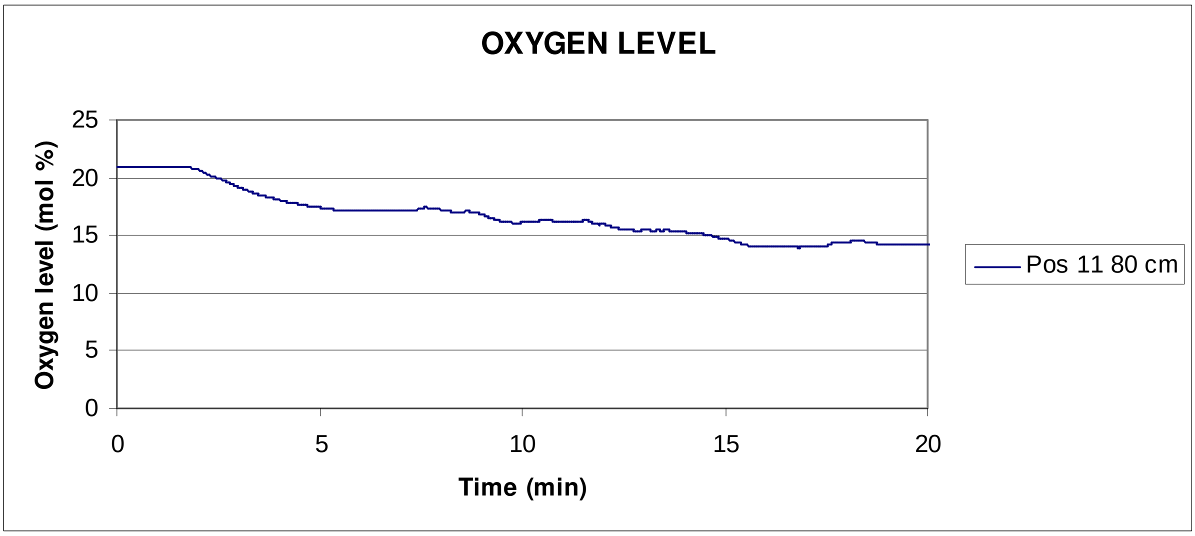


Diagram N 4: Oxygen level.

Appendix O - Experimental Results - Test 4

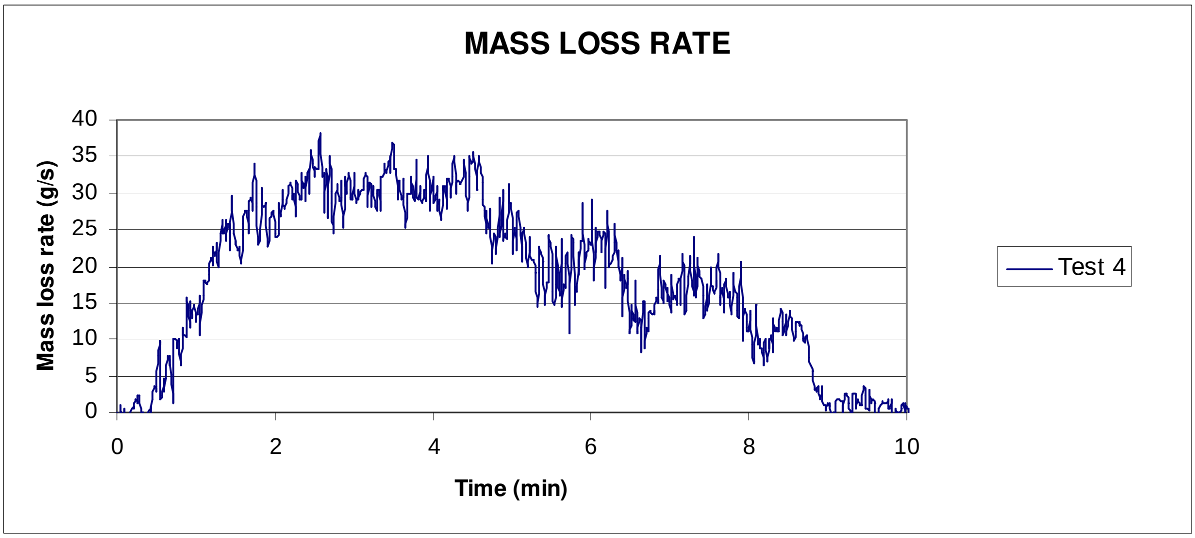


Diagram O 1: Mass loss rate.

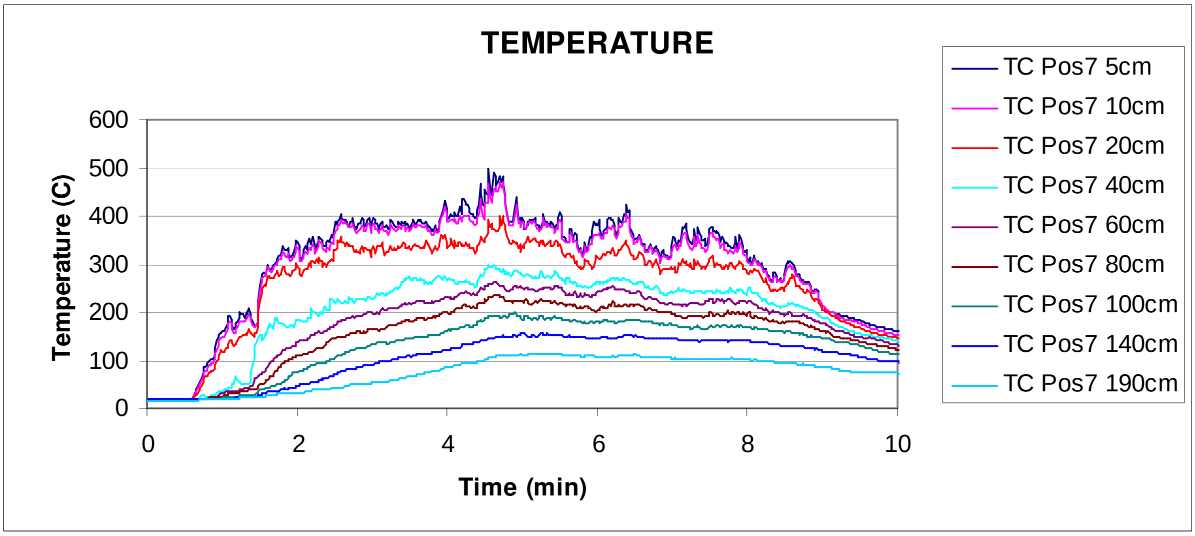


Diagram O 2: Temperature profiles

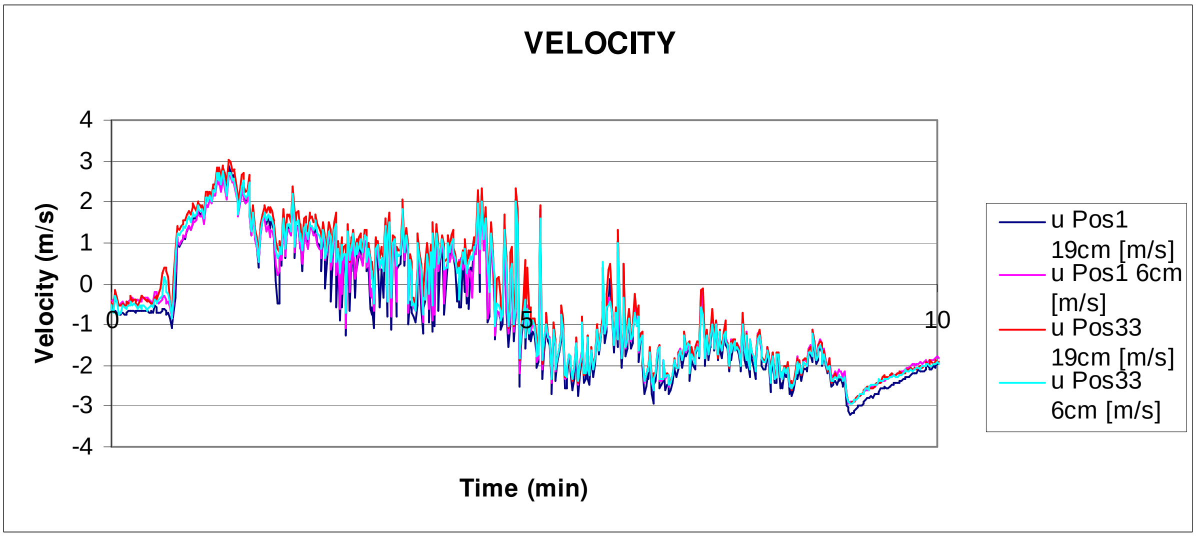


Diagram O 3: Velocity profiles.

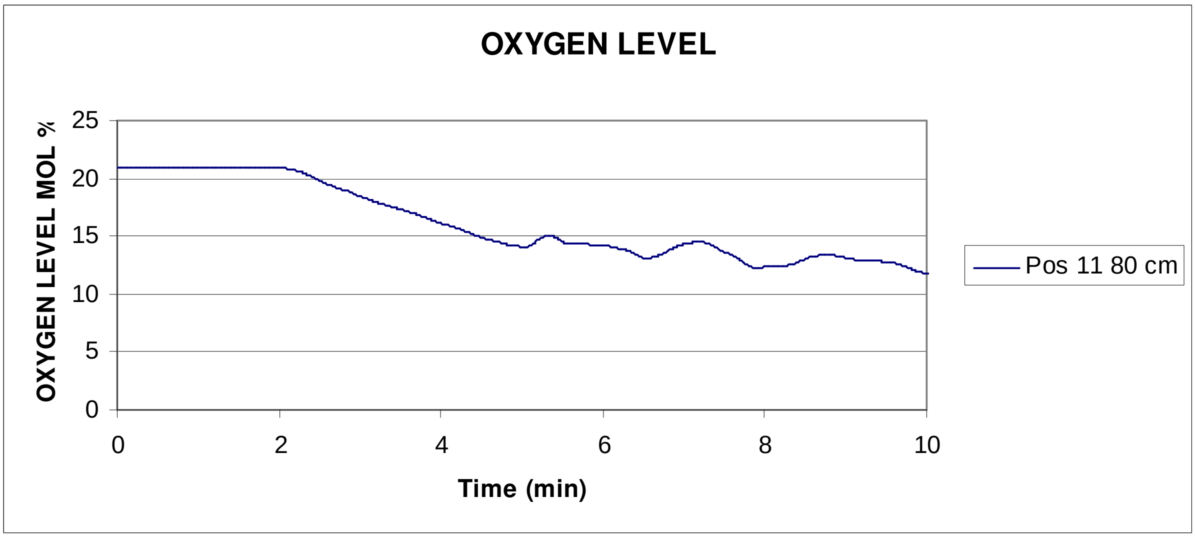


Diagram O 4: Oxygen level.

Appendix P - Experimental Results - Test 5

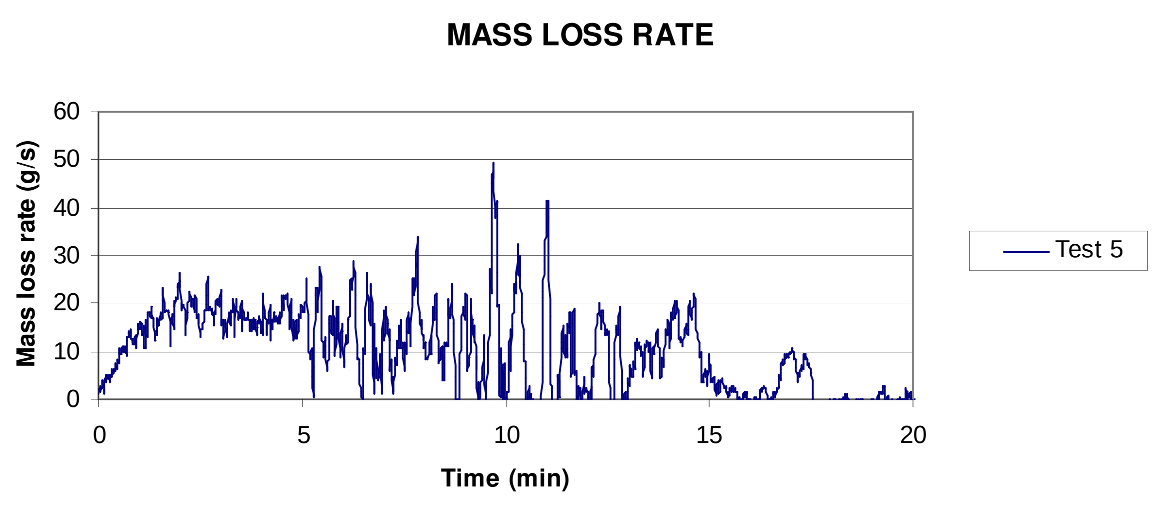


Diagram P 1: Mass loss rate.

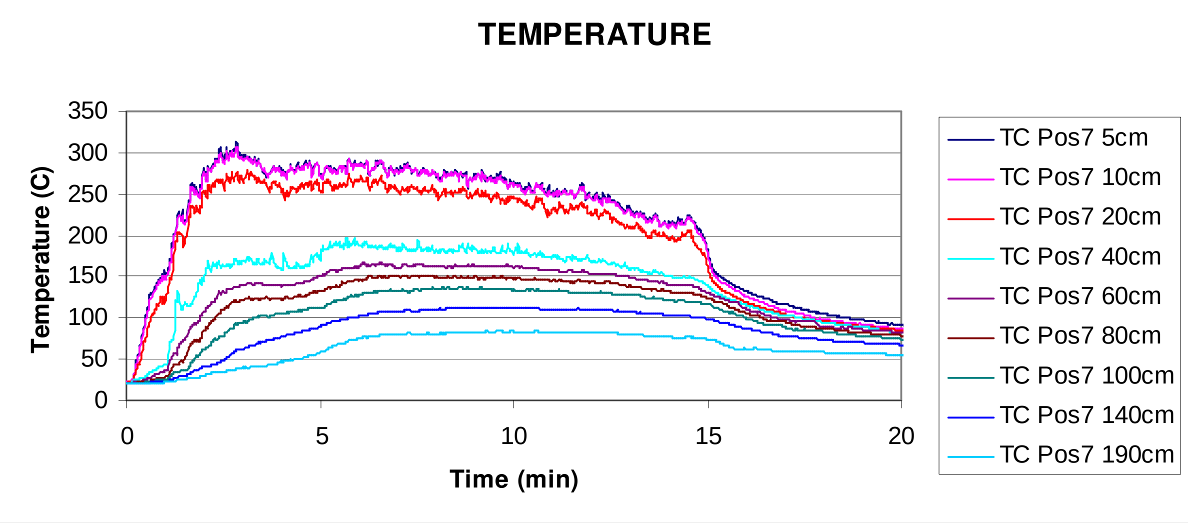


Diagram P 2: Temperature profiles

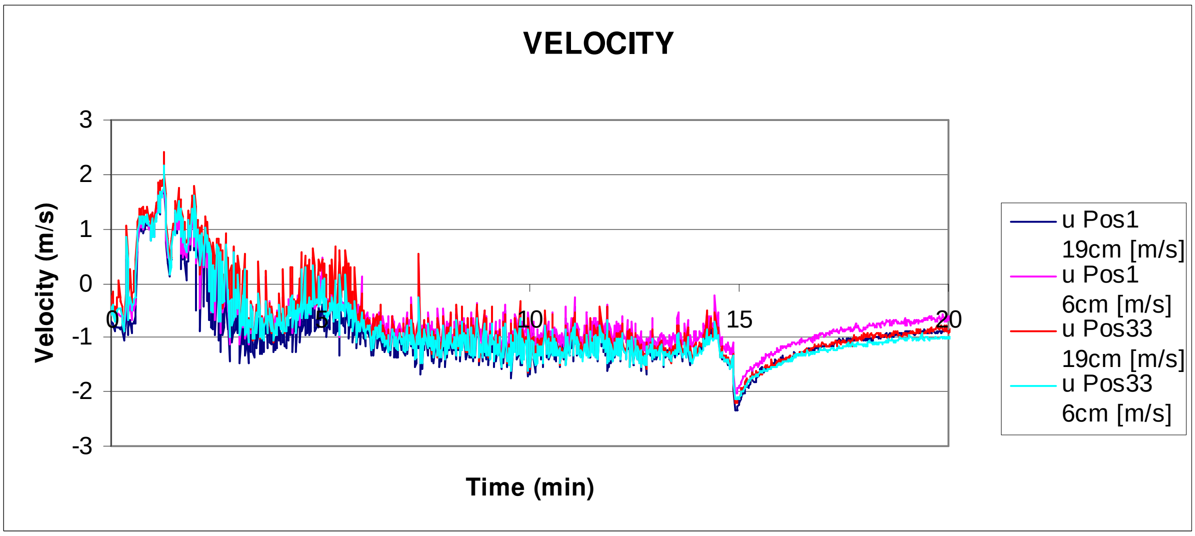


Diagram P 3: Velocity profiles

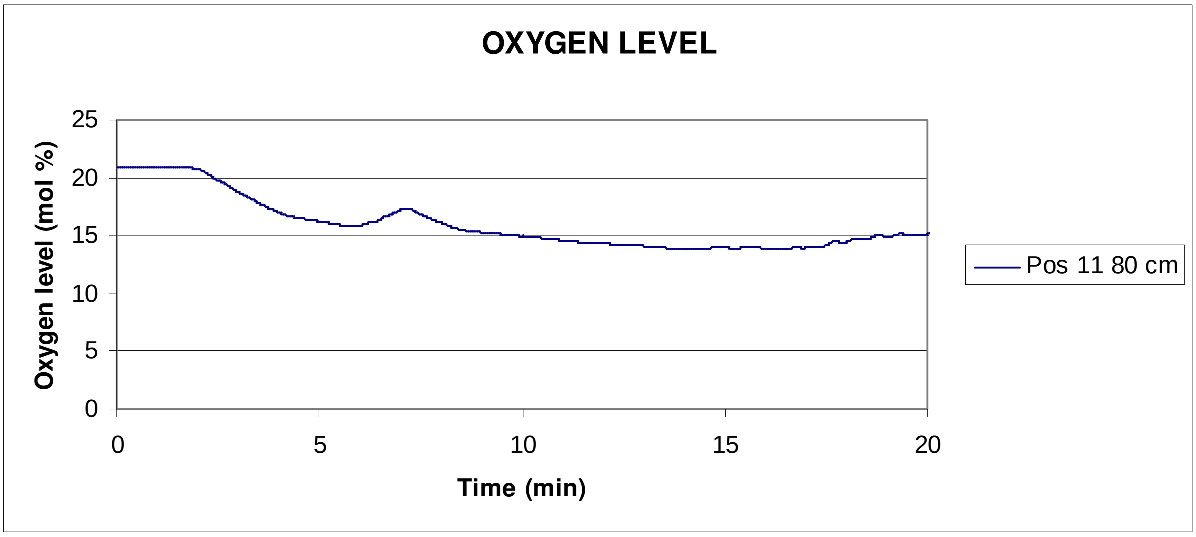


Diagram P 4: Oxygen level.

Appendix Q - Experimental Results - Test 6

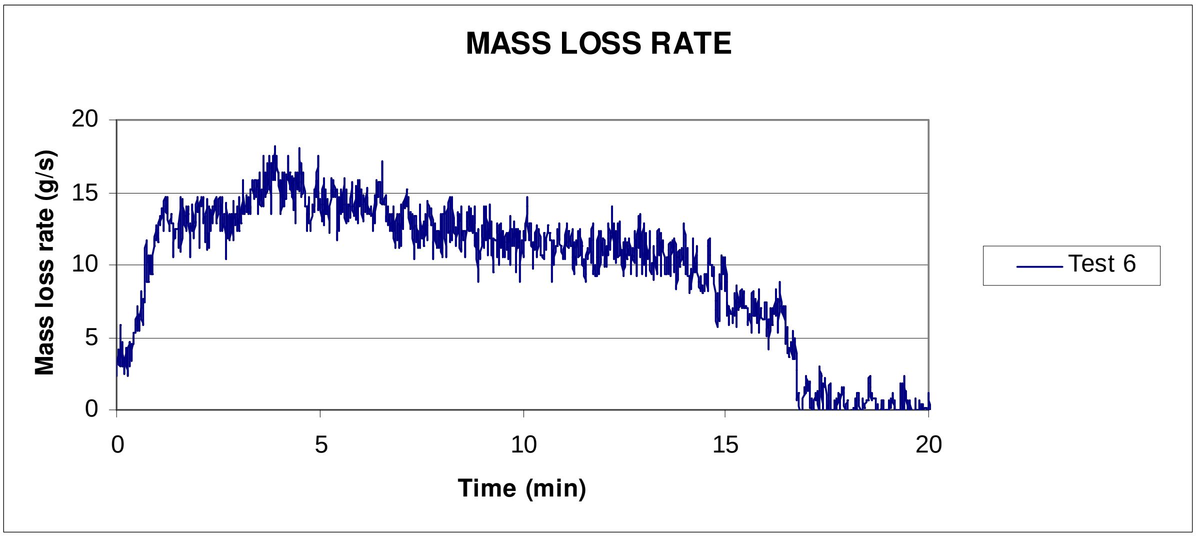


Diagram Q 1: Mass loss rate.

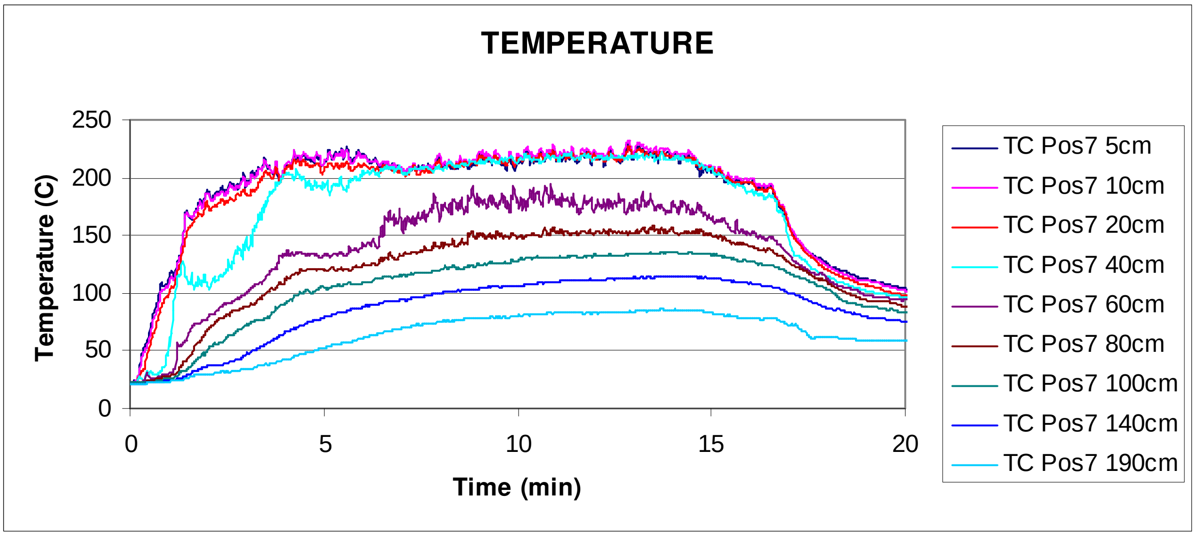


Diagram Q 2: Temperature profiles.

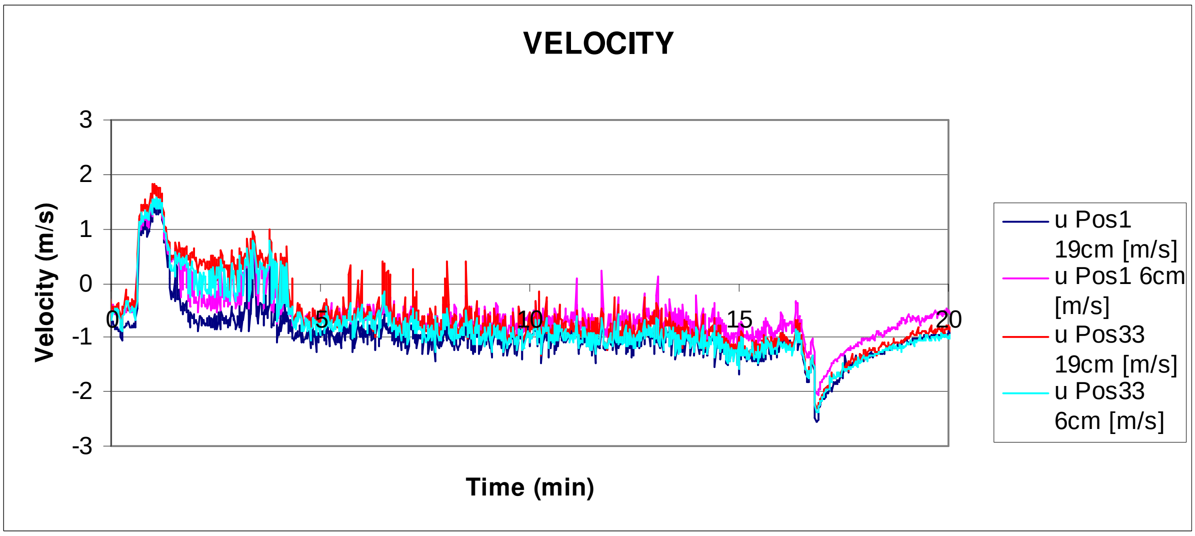


Diagram Q 3: Velocity profiles

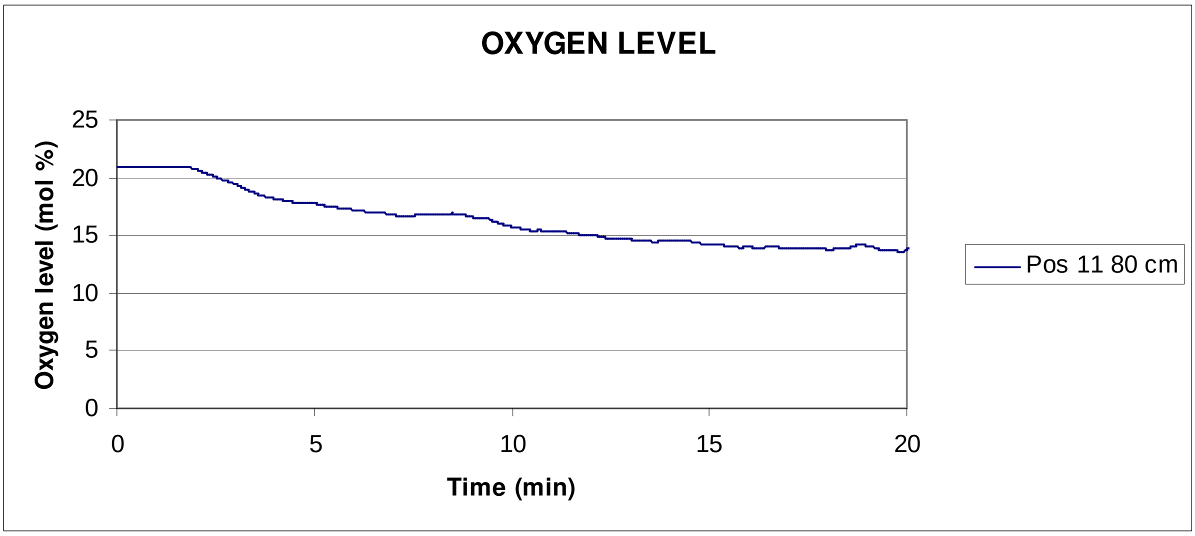


Diagram Q 4 Oxygen level.

Appendix R - Experimental Results - Test 7

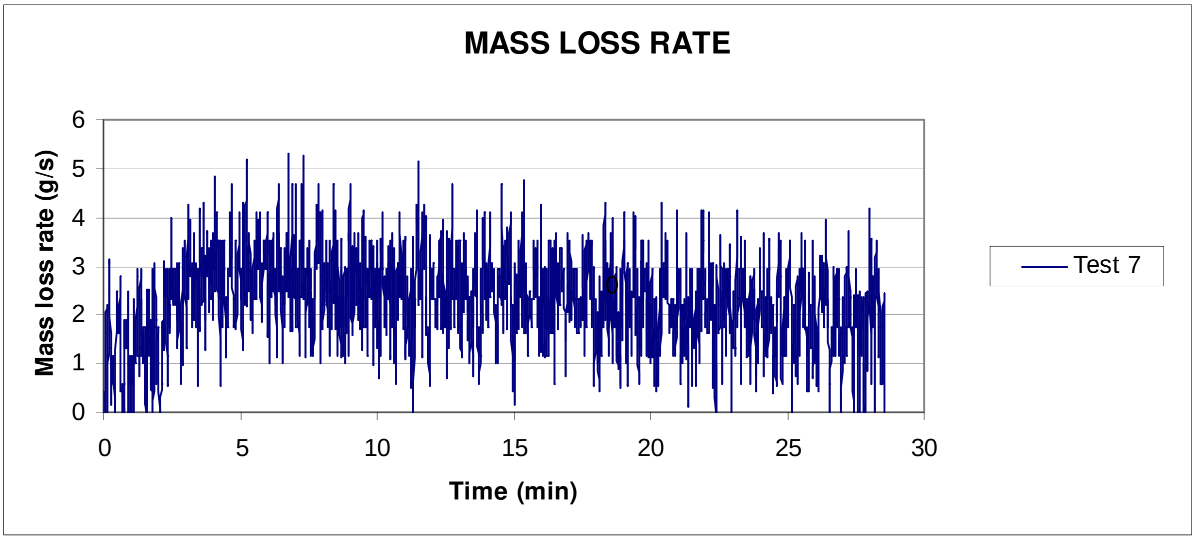


Diagram R 1 Mass loss rate

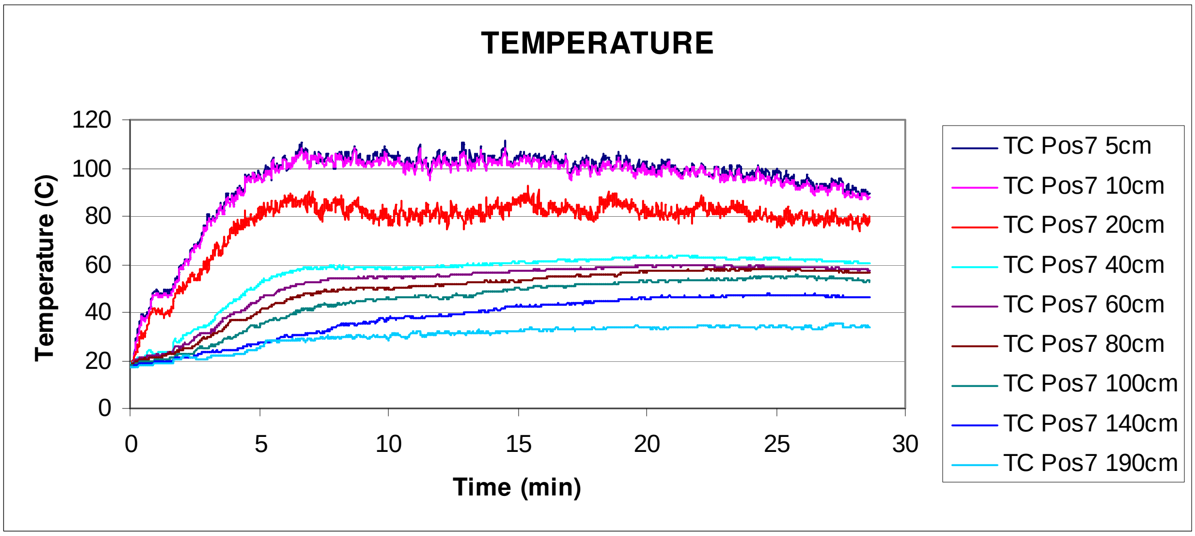


Diagram R 2 Temperature profiles

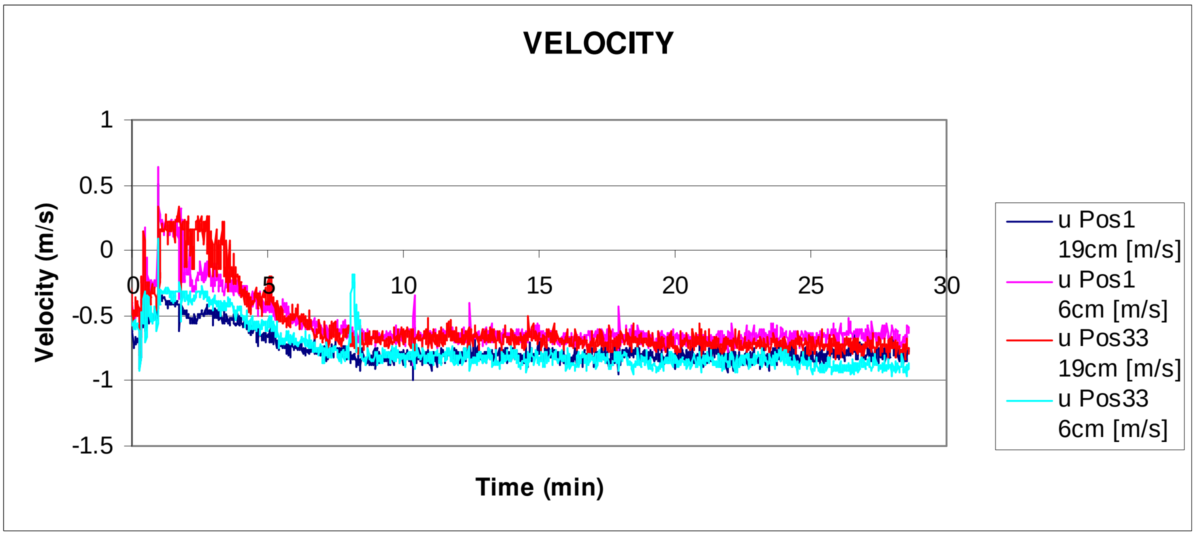


Diagram R 3: Velocity profiles.

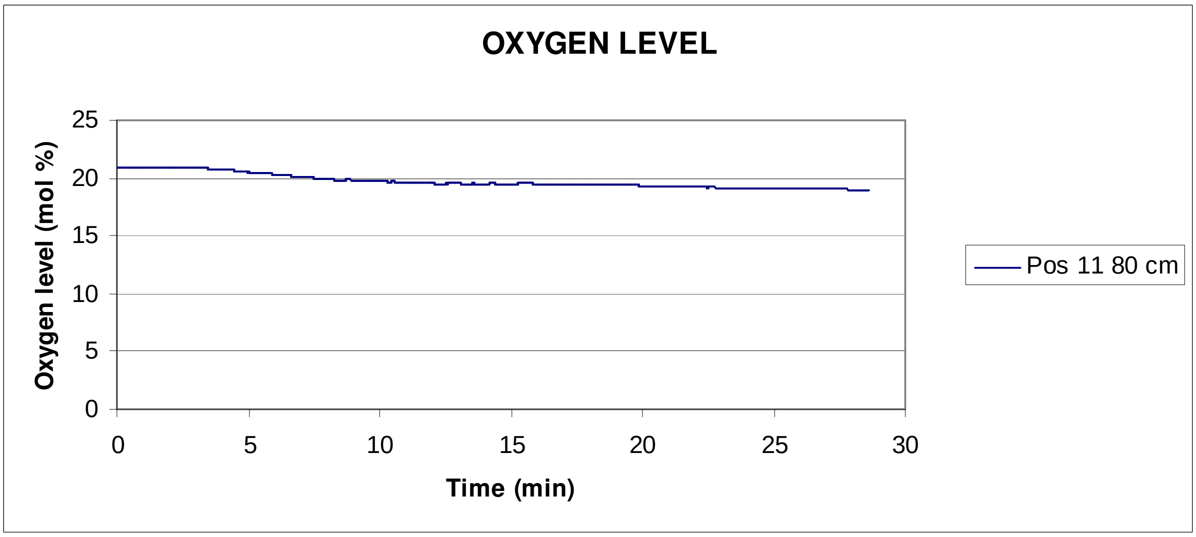


Diagram R 4: Oxygen level.

Appendix S - Experimental Results - Test 8

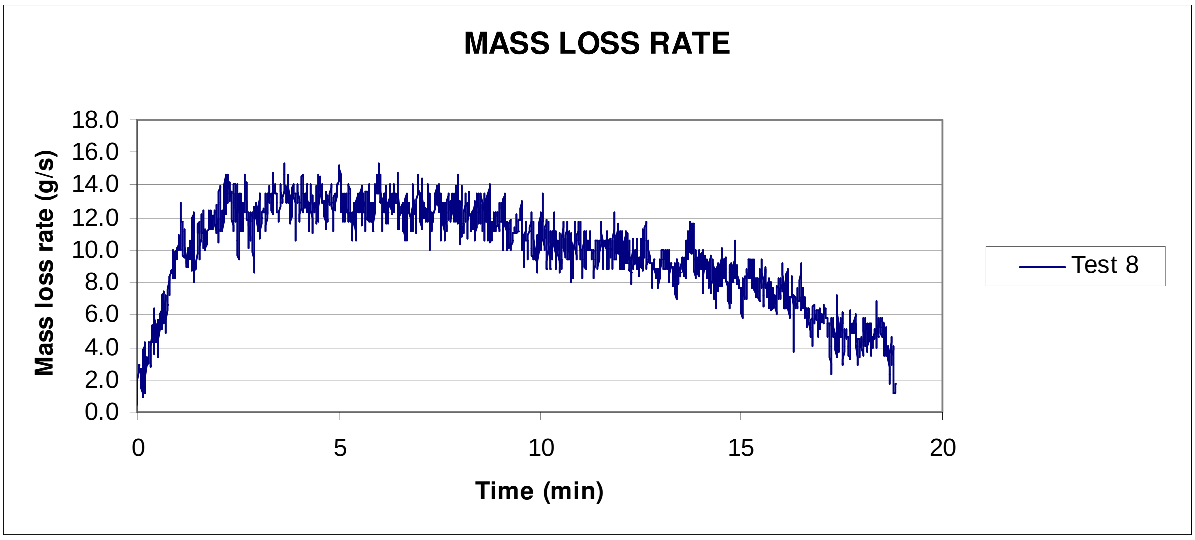


Diagram S 1: Mass loss rate

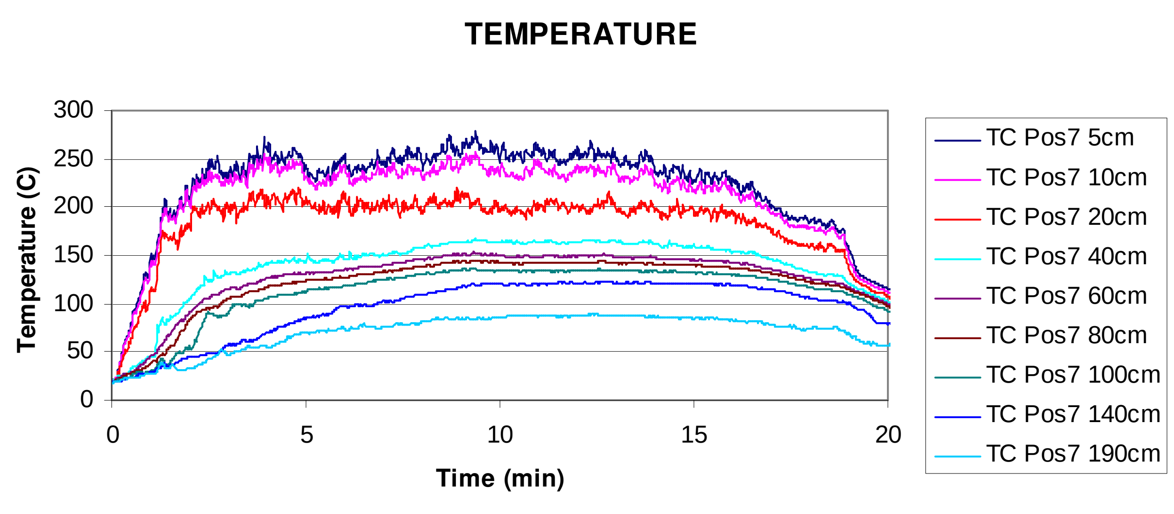


Diagram S 2: Temperature profiles.

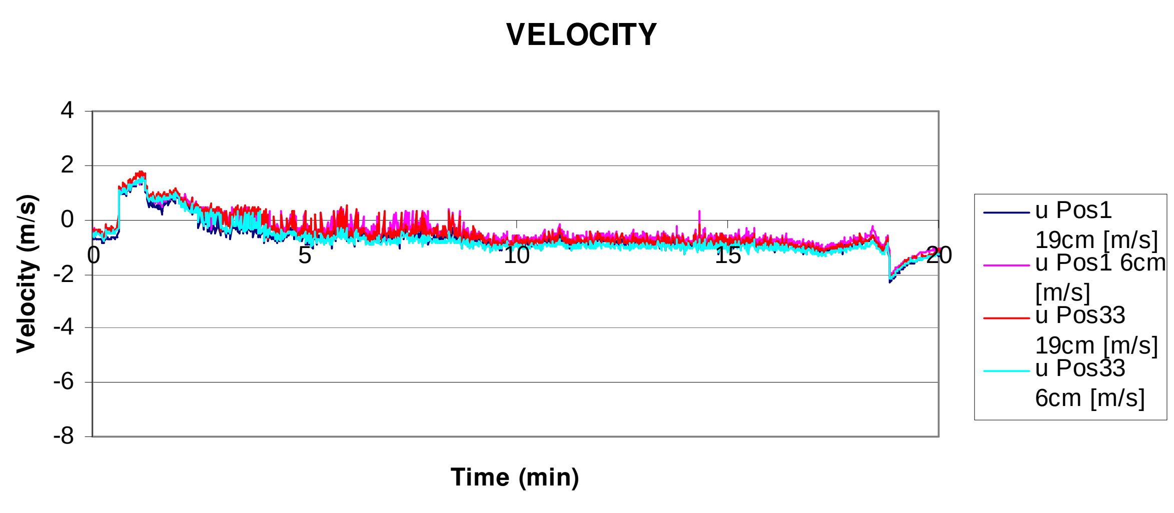


Diagram S 3: Velocity profiles

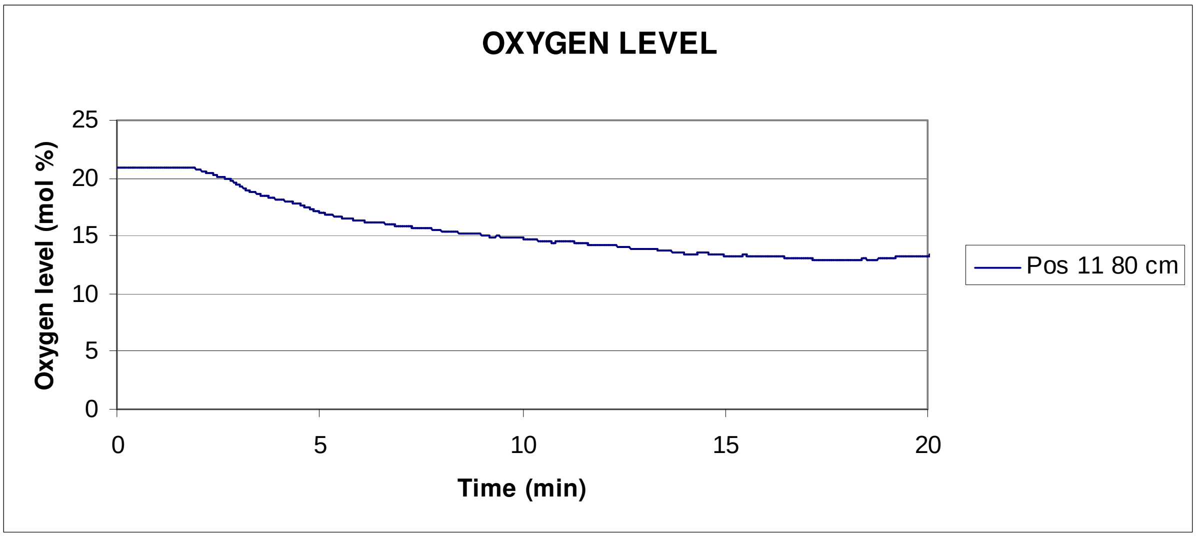


Diagram S 4: Oxygen level.

Appendix T - Experimental Results - Test 9

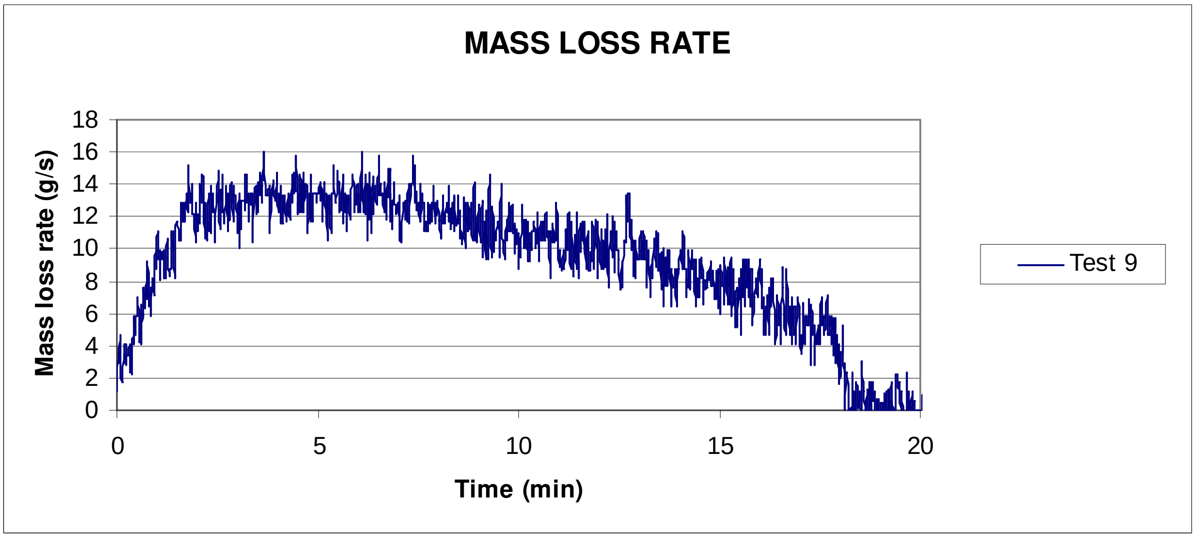


Diagram T 1: Mass loss rate.

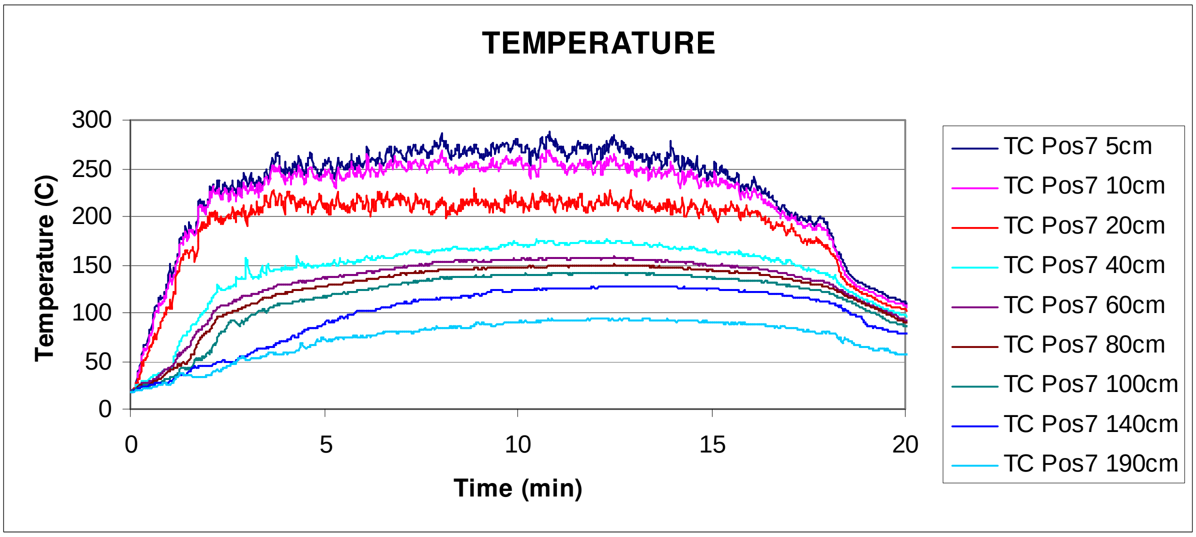


Diagram T 2. Temperature profiles

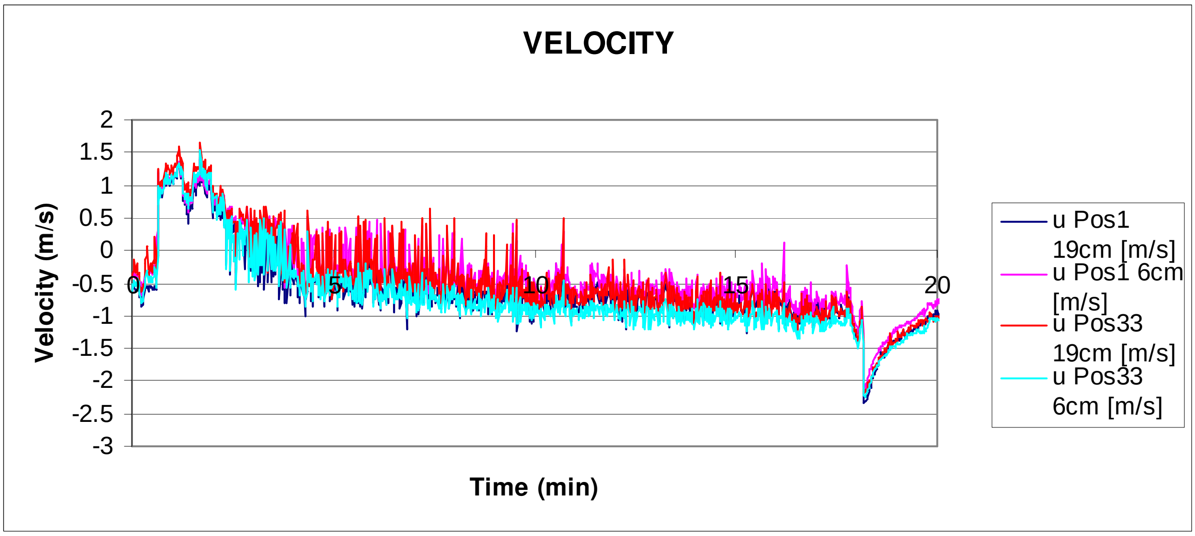


Diagram T 3: Velocity profiles.

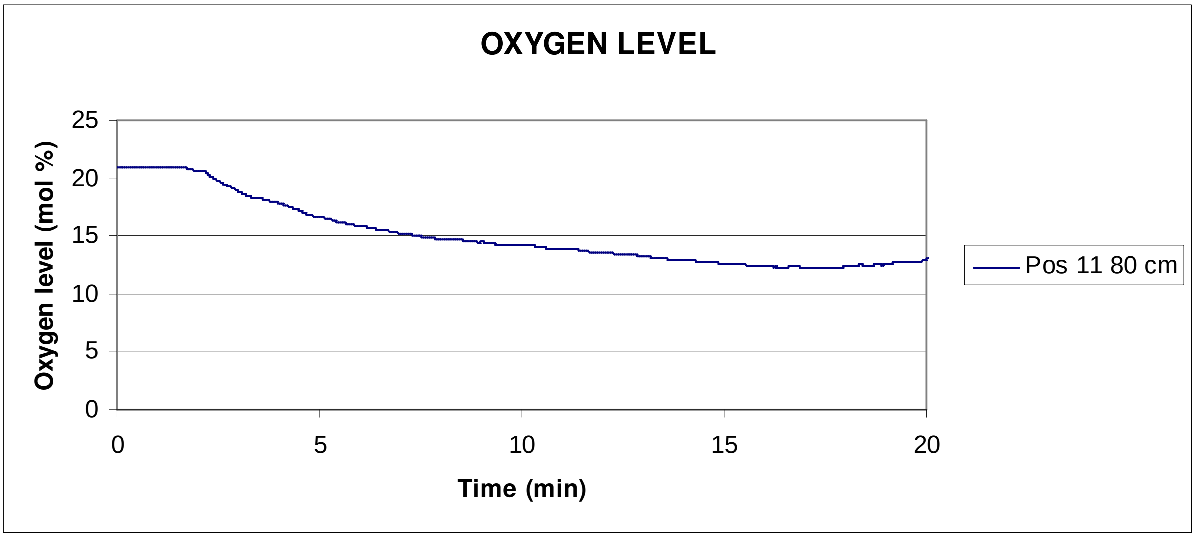


Diagram T 4: Oxygen level.

Appendix U - Experimental Results - Test 10

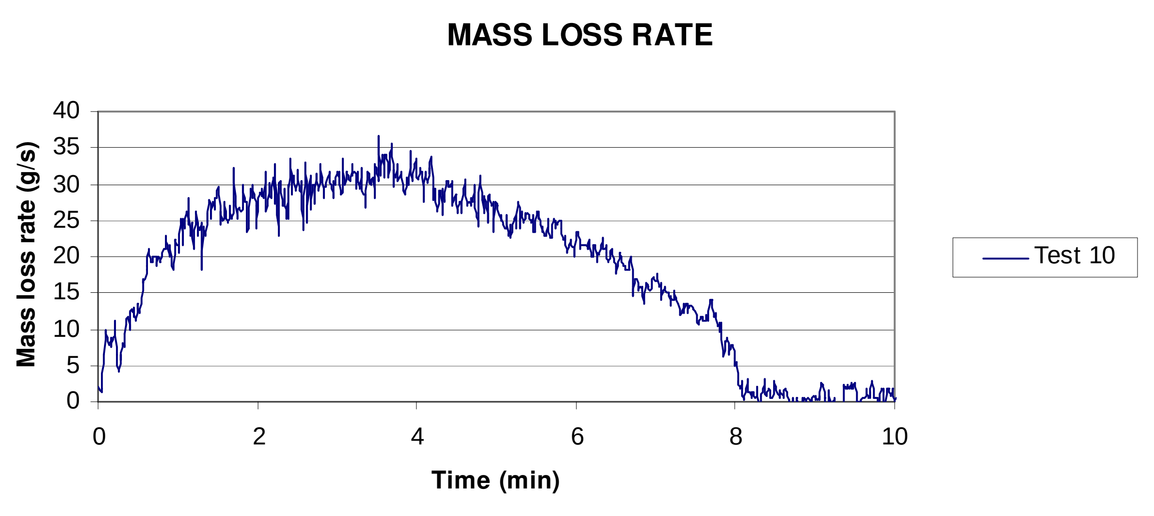


Diagram U 1: Mass loss rate.

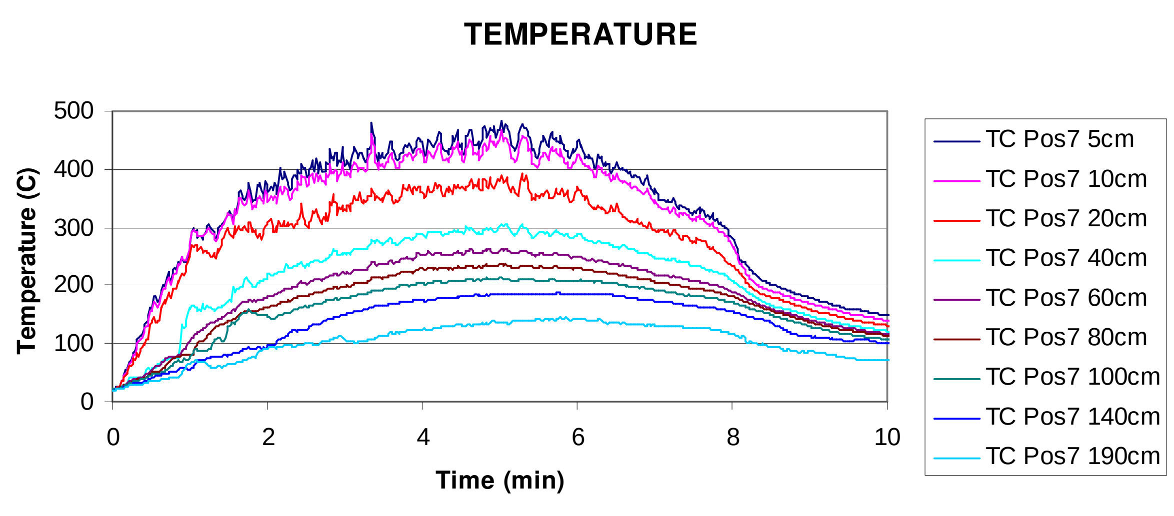


Diagram U 2: Temperature profiles

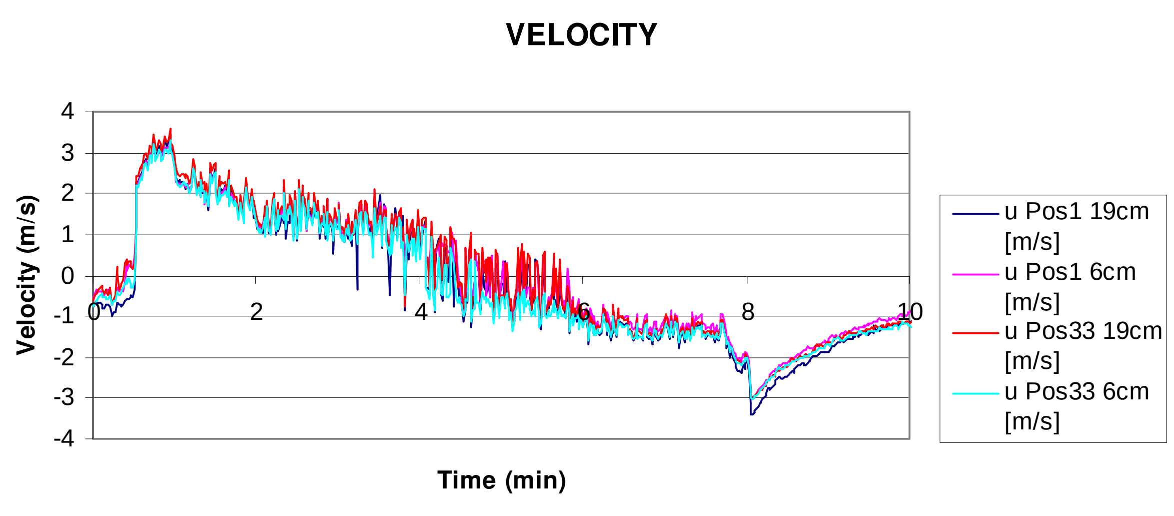


Diagram U 3: Velocity profiles

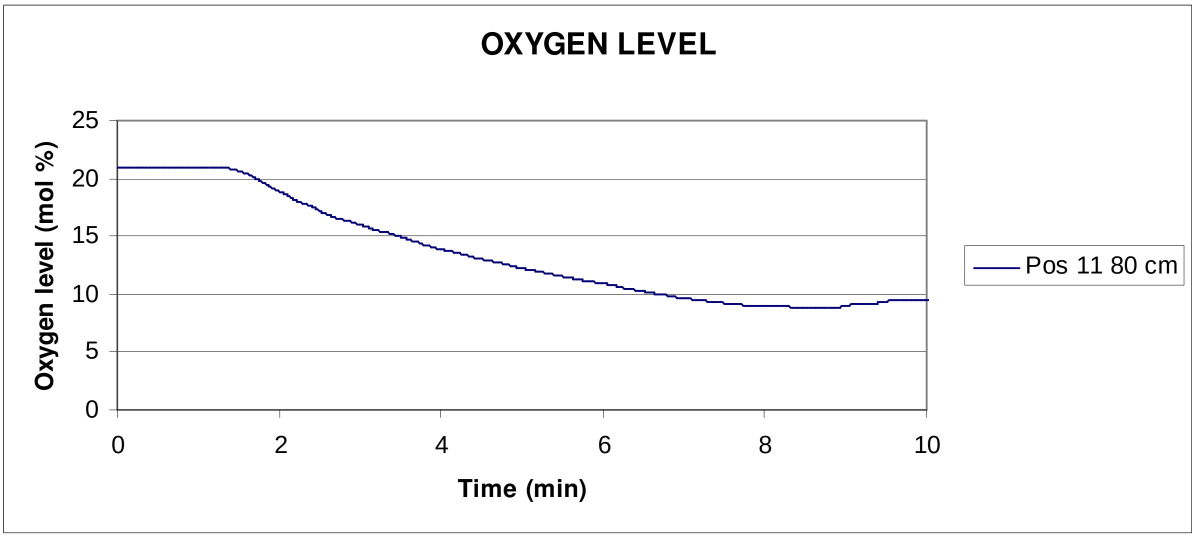


Diagram U 4: Oxygen level.

Appendix V - Experimental Results - Test 11

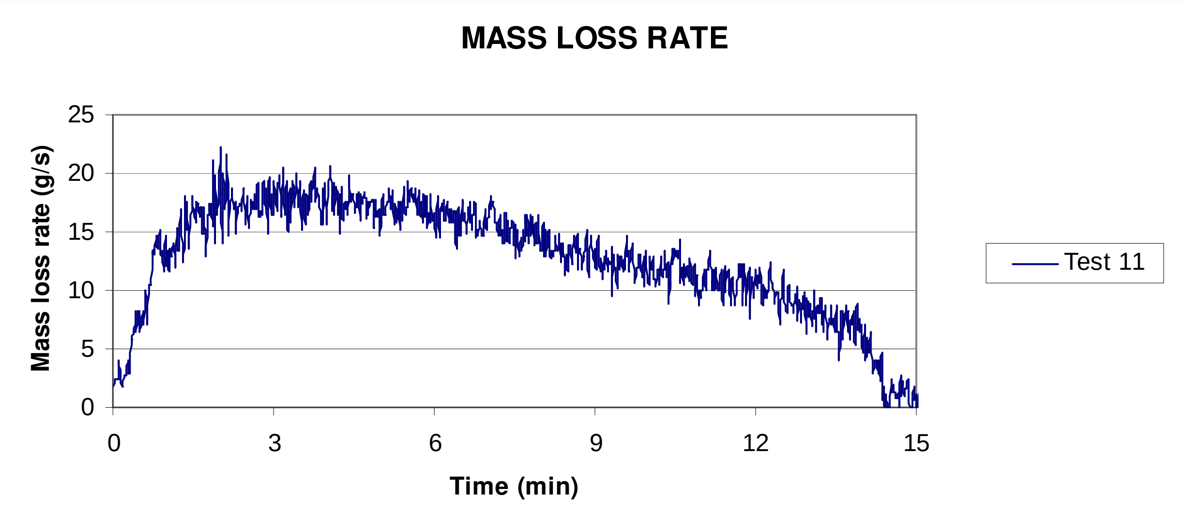


Diagram V 1: Mass loss rate

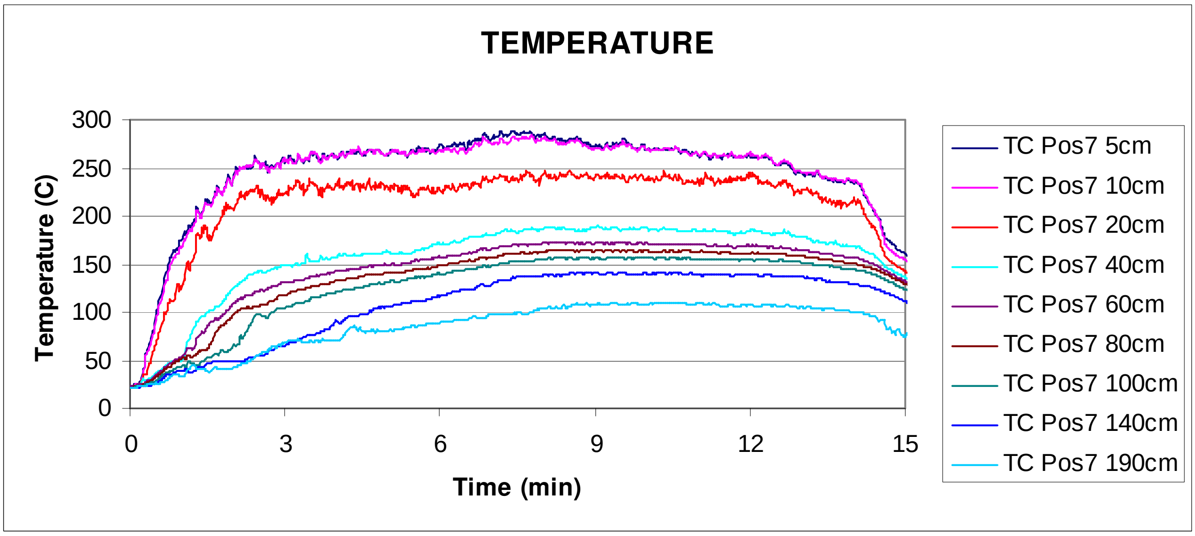


Diagram V 2: Temperature profiles

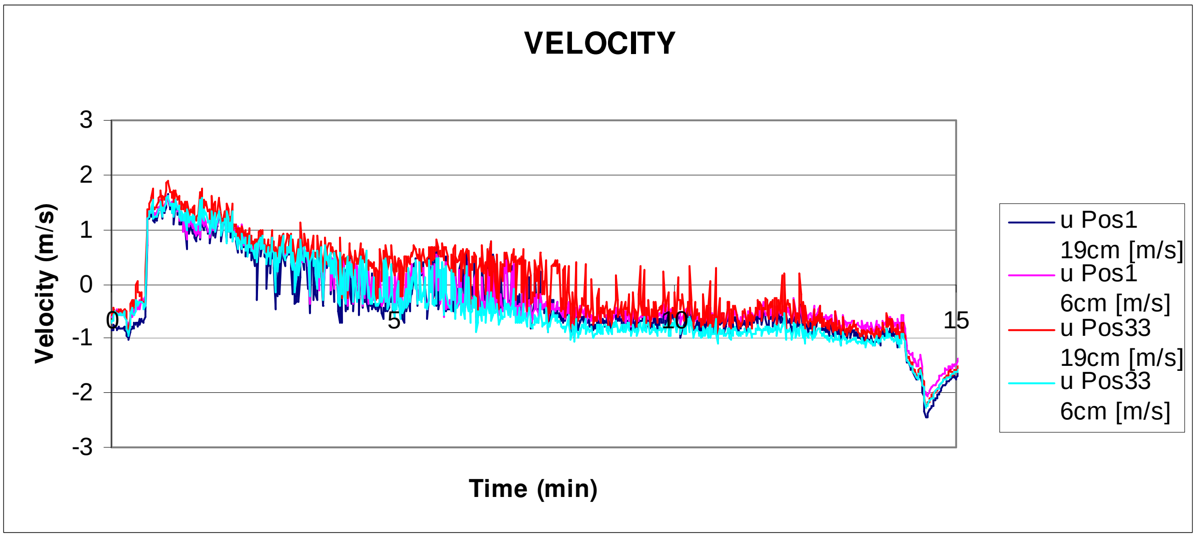


Diagram V 3: Velocity profiles.

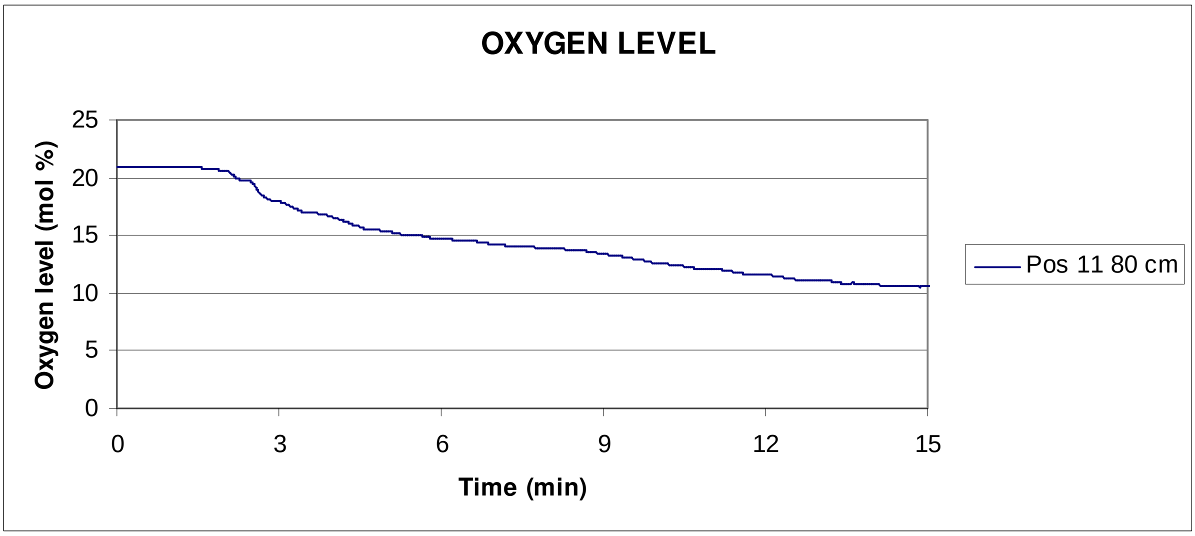


Diagram V 4: Oxygen level.

Appendix W – FDS script file for the Base scenario case 10

The output input has been removed and can be found in *"Smoke spread and gas temperatures during fires in retail premises- Experiments and CFD Simulations"* (Lönnermark & Björklund 2009).

```
&HEAD CHID='CASE10_8N_BAS',TITLE='CASE10_8N_BAS'  / All output files will
have names beginning with "".

&TIME T_END=540.0, SYNCHRONIZE=.FALSE. / Time when finished (length of
simulation)

&MESH ID='Brand', COLOR='YELLOW', IJK=40,40,24,  XB= 1.00, 3.00,  4.00,
6.00, 0.40, 1.60/
&MESH ID='Brand2', COLOR='YELLOW', IJK=40,40,24,  XB= 1.00, 3.00,  4.00,
6.00, 1.60, 2.80/
&MESH ID='Söder om brand',         IJK=100,40,24,  XB= 1.00, 11.00,  0.00,
4.00, 0.40,2.80/
&MESH ID='Norr om brand',          IJK=180,20,24,  XB= 1.00, 19.00,  6.00,
8.00, 0.40,2.80/
&MESH ID='Bakom brand',            IJK=30,80,32,  XB= -2.00, 1.00,  0.00,
8.00, -0.40,2.80/
&MESH ID='Hyllvolym',              IJK=80,20,24, XB= 3.00, 11.00, 4.00,
6.00,  0.40,2.80/
&MESH ID='HYLLVOLYM 2',            IJK=80,60,24,  XB=11.00, 19.00, 0.00,
6.00, 0.40,2.80/
&MESH ID='UNDER BRAND',            IJK=180,80,8,  XB= 1.00, 19.00, 0.00,
8.00, -0.40,0.40/

&MISC    SURF_DEFAULT='WALL', RADIATION=.TRUE., TMPA=17.8, RESTART=.FALSE.,
CO_PRODUCTION=.FALSE. /

&DUMP NFRAMES=540, FLUSH_FILE_BUFFERS=.TRUE./

&MATL ID='PROMATECT'
      SPECIFIC_HEAT_RAMP='Promatect_SPECIFIC_HEAT_RAMP'
      CONDUCTIVITY_RAMP='Promatect_CONDUCTIVITY_RAMP'
      DENSITY=860./
&RAMP ID='Promatect_SPECIFIC_HEAT_RAMP', T=20., F=0.74/
&RAMP ID='Promatect_SPECIFIC_HEAT_RAMP', T=200., F=0.92/
&RAMP ID='Promatect_SPECIFIC_HEAT_RAMP', T=400., F=1.03/
&RAMP ID='Promatect_CONDUCTIVITY_RAMP', T=20., F=0.1700/
&RAMP ID='Promatect_CONDUCTIVITY_RAMP', T=200., F=0.2140/
&RAMP ID='Promatect_CONDUCTIVITY_RAMP', T=400., F=0.2410/

&MATL ID='MASTERBOARD',
      CONDUCTIVITY=0.22
      SPECIFIC_HEAT=1.09
      DENSITY=910. /

&MATL ID='ROXULL INSULATION'
      CONDUCTIVITY=0.039
      SPECIFIC_HEAT=0.79
      DENSITY=180. / kg/m3

&MATL ID='CONCRETE'
      CONDUCTIVITY=1.0
      SPECIFIC_HEAT=0.88
      DENSITY=2100. /

&MATL ID='HEPTANE'
```

```
       DENSITY=680./

&SURF ID='FLOOR'
      MATL_ID   ='CONCRETE'
      COLOR   ='GRAY'
      CONVECTIVE_HEAT_FLUX=5
      BACKING   ='EXPOSED'
      EMISSIVITY=0.9
      THICKNESS=0.30,/

&SURF ID='WALL'
      MATL_ID   ='PROMATECT'
      COLOR   ='GRAY'
      CONVECTIVE_HEAT_FLUX=5
      BACKING   ='EXPOSED'
      EMISSIVITY=0.9
      THICKNESS=0.010,/

&SURF ID    ='TAK MED ISOLERING'
      MATL_ID   ='ROXULL INSULATION','PROMATECT'
      COLOR   = 'GREEN'
      BACKING   ='EXPOSED'
      EMISSIVITY=0.9
      CONVECTIVE_HEAT_FLUX=5
      THICKNESS=0.02, 0.01/

&REAC ID='HEPTANE',
      C=7.00,
      H=16.00,
      SOOT_YIELD=0.015
      CO_YIELD= 0.006
      HEAT_OF_COMBUSTION= 44560/

&RADI RADIATIVE_FRACTION=0.3 /

&SURF ID='FIRE'
      MLRPUA=0.0946745
      RAMP_Q='MLR RAMP'
      COLOR= 'RED'/


&RAMP ID='MLR RAMP', T=0.0, F=0.049/
&RAMP ID='MLR RAMP', T=6.0, F=0.195/
&RAMP ID='MLR RAMP', T=12.0, F=0.171/
&RAMP ID='MLR RAMP', T=18.0, F=0.226/
&RAMP ID='MLR RAMP', T=24.0, F=0.287/
&RAMP ID='MLR RAMP', T=30.0, F=0.244/
&RAMP ID='MLR RAMP', T=36.0, F=0.573/
&RAMP ID='MLR RAMP', T=42.0, F=0.463/
&RAMP ID='MLR RAMP', T=48.0, F=0.512/
&RAMP ID='MLR RAMP', T=54.0, F=0.512/
&RAMP ID='MLR RAMP', T=60.0, F=0.616/
&RAMP ID='MLR RAMP', T=66.0, F=0.629/
&RAMP ID='MLR RAMP', T=72.0, F=0.536/
&RAMP ID='MLR RAMP', T=78.0, F=0.543/
&RAMP ID='MLR RAMP', T=84.0, F=0.635/
&RAMP ID='MLR RAMP', T=90.0, F=0.751/
&RAMP ID='MLR RAMP', T=96.0, F=0.659/
&RAMP ID='MLR RAMP', T=102.0, F=0.659/
&RAMP ID='MLR RAMP', T=108.0, F=0.659/
&RAMP ID='MLR RAMP', T=114.0, F=0.682/
```

```
&RAMP ID='MLR RAMP', T=120.0, F=0.659/
&RAMP ID='MLR RAMP', T=126.0, F=0.780/
&RAMP ID='MLR RAMP', T=132.0, F=0.665/
&RAMP ID='MLR RAMP', T=138.0, F=0.775/
&RAMP ID='MLR RAMP', T=144.0, F=0.683/
&RAMP ID='MLR RAMP', T=150.0, F=0.683/
&RAMP ID='MLR RAMP', T=156.0, F=0.689/
&RAMP ID='MLR RAMP', T=162.0, F=0.829/
&RAMP ID='MLR RAMP', T=168.0, F=0.823/
&RAMP ID='MLR RAMP', T=174.0, F=0.708/
&RAMP ID='MLR RAMP', T=180.0, F=0.732/
&RAMP ID='MLR RAMP', T=186.0, F=0.878/
&RAMP ID='MLR RAMP', T=192.0, F=0.708/
&RAMP ID='MLR RAMP', T=198.0, F=0.683/
&RAMP ID='MLR RAMP', T=204.0, F=0.829/
&RAMP ID='MLR RAMP', T=210.0, F=0.806/
&RAMP ID='MLR RAMP', T=216.0, F=0.755/
&RAMP ID='MLR RAMP', T=222.0, F=0.878/
&RAMP ID='MLR RAMP', T=228.0, F=0.731/
&RAMP ID='MLR RAMP', T=234.0, F=0.708/
&RAMP ID='MLR RAMP', T=240.0, F=0.909/
&RAMP ID='MLR RAMP', T=246.0, F=0.726/
&RAMP ID='MLR RAMP', T=252.0, F=0.804/
&RAMP ID='MLR RAMP', T=258.0, F=0.658/
&RAMP ID='MLR RAMP', T=264.0, F=0.708/
&RAMP ID='MLR RAMP', T=270.0, F=0.707/
&RAMP ID='MLR RAMP', T=276.0, F=0.683/
&RAMP ID='MLR RAMP', T=282.0, F=0.634/
&RAMP ID='MLR RAMP', T=288.0, F=0.714/
&RAMP ID='MLR RAMP', T=294.0, F=0.658/
&RAMP ID='MLR RAMP', T=300.0, F=0.756/
&RAMP ID='MLR RAMP', T=306.0, F=0.531/
&RAMP ID='MLR RAMP', T=312.0, F=0.585/
&RAMP ID='MLR RAMP', T=318.0, F=0.664/
&RAMP ID='MLR RAMP', T=324.0, F=0.635/
&RAMP ID='MLR RAMP', T=330.0, F=0.610/
&RAMP ID='MLR RAMP', T=336.0, F=0.585/
&RAMP ID='MLR RAMP', T=342.0, F=0.579/
&RAMP ID='MLR RAMP', T=348.0, F=0.658/
&RAMP ID='MLR RAMP', T=354.0, F=0.488/
&RAMP ID='MLR RAMP', T=360.0, F=0.543/
&RAMP ID='MLR RAMP', T=366.0, F=0.604/
&RAMP ID='MLR RAMP', T=372.0, F=0.439/
&RAMP ID='MLR RAMP', T=378.0, F=0.561/
&RAMP ID='MLR RAMP', T=384.0, F=0.512/
&RAMP ID='MLR RAMP', T=390.0, F=0.488/
&RAMP ID='MLR RAMP', T=396.0, F=0.439/
&RAMP ID='MLR RAMP', T=402.0, F=0.488/
&RAMP ID='MLR RAMP', T=408.0, F=0.341/
&RAMP ID='MLR RAMP', T=414.0, F=0.366/
&RAMP ID='MLR RAMP', T=420.0, F=0.445/
&RAMP ID='MLR RAMP', T=426.0, F=0.336/
&RAMP ID='MLR RAMP', T=432.0, F=0.415/
&RAMP ID='MLR RAMP', T=438.0, F=0.274/
&RAMP ID='MLR RAMP', T=444.0, F=0.360/
&RAMP ID='MLR RAMP', T=450.0, F=0.275/
&RAMP ID='MLR RAMP', T=456.0, F=0.287/
&RAMP ID='MLR RAMP', T=462.0, F=0.366/
&RAMP ID='MLR RAMP', T=468.0, F=0.165/
&RAMP ID='MLR RAMP', T=474.0, F=0.250/
&RAMP ID='MLR RAMP', T=480.0, F=0.049/
```

```
&RAMP ID='MLR RAMP', T=486.0, F=0.030/
&RAMP ID='MLR RAMP', T=492.0, F=0.00/
&RAMP ID='MLR RAMP', T=498.0, F=0.073/
&RAMP ID='MLR RAMP', T=504.0, F=0.031/
&RAMP ID='MLR RAMP', T=510.0, F=0.091/
&RAMP ID='MLR RAMP', T=516.0, F=0.00/
&RAMP ID='MLR RAMP', T=522.0, F=0.00/
&RAMP ID='MLR RAMP', T=528.0, F=0.024/
&RAMP ID='MLR RAMP', T=534.0, F=0.00/
&RAMP ID='MLR RAMP', T=540.0, F=0.031/

&VENT XB= 1.70, 2.35, 4.80, 5.45 ,0.60, 0.60, SURF_ID='FIRE'/

&OBST XB=-0.10,  0.00, 0.10, 7.60, 0.00, 2.50, SURF_ID='WALL'/ Backwall
&OBST XB=-0.10, 18.00, 7.60, 7.70, 0.00, 2.50, SURF_ID='WALL'/ North Wall
&OBST XB=-0.10, 18.00, 0.00, 0.10, 0.00, 2.50, SURF_ID='WALL'/ South Wall
&OBST XB= 5.00, 18.00, 0.00, 7.70, 2.40, 2.50, SURF_ID='WALL'/ Ceiling
&OBST XB=-0.10,  5.00, 0.00, 7.70, 2.40, 2.50, SURF_ID='TAK MED ISOLERING'/
Ceiling ÖVER BRAND
&OBST XB=-3.10, 20.90, 0.00, 7.70,-0.40, 0.00, SURF_ID='FLOOR'/ Floor
&OBST XB= 1.70, 2.35, 4.80, 5.45 ,0.45, 0.60, SURF_ID='INERT'/ Firebox
&OBST XB= 1.60, 2.40, 4.70, 5.50, 0.40, 0.45, SURF_ID='INERT'/ Firebox
&OBST XB=18.00, 18.10, 0.00, 7.70, 0.00, 2.50, SURF_ID='WALL'/ FRONTWALL
LIGGER 10 CM NÄRMARE BRANDEN ÄN DE SKALL


&HOLE XB=  18.0, 18.10, 7.00, 7.70, 0.00, 2.00, COLOR='RED',
DEVC_ID='TIMER1'   / doorwall door 10 CM BREDARE
&DEVC XYZ= 18.0,  7.30,  1.0, ID='TIMER1', SETPOINT=30, QUANTITY='TIME',
INITIAL_STATE=.TRUE./ ÄNDRAD
&HOLE XB= -0.10,  0.00, 4.00, 4.50, 0.00, 0.30, / 5 cm mer norrut samt 5 cm
högre
&HOLE XB= 18.00, 18.10, 4.00, 4.50, 0.00, 0.30, / 5 cm mer norrut samt 5 cm
högre

&VENT MB='XMAX', SURF_ID='OPEN'/
&VENT MB='YMAX', SURF_ID='OPEN'/
&VENT MB='ZMAX', SURF_ID='OPEN'/
&VENT MB='XMIN', SURF_ID='OPEN'/
&VENT MB='YMIN', SURF_ID='OPEN'/
&VENT MB='ZMIN', SURF_ID='OPEN'/
```

Appendix X – Number and sizes of the grids in the Base scenario

Mesh 1	**Length**	**Grids**	**Grid size**		**Mesh 5**	**Length**	**Grids**	**Grid size**
x	2	40	0.05		X	3	30	0.1
y	2	40	0.05		Y	8	80	0.1
z	1.2	24	0.05		Z	3.2	32	0.1
		38400					76800	
Mesh 2	**Length**	**Grids**	**Grid size**		**Mesh 6**	**Length**	**Grids**	**Grid size**
x	2	40	0.05		x	8	80	0.1
y	2	40	0.05		y	2	20	0.1
z	1.2	24	0.05		z	2.4	24	0.1
		38400					38400	
Mesh 3	**Length**	**Grids**	**Grid size**		**Mesh 7**	**Length**	**Grids**	**Grid size**
x	10	100	0.1		x	8	80	0.1
y	4	40	0.1		y	6	60	0.1
z	2.4	24	0.1		z	2.4	24	0.1
		96000					115200	
Mesh 4	**Length**	**Grids**	**Grid size**		**Mesh 8**	**Length**	**Grids**	**Grid size**
x	18	180	0.1		x	18	180	0.1
y	2	20	0.1		y	8	80	0.1
z	2.4	24	0.1		z	0.8	8	0.1
		86400					115200	
					Totalt		604800	