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INVESTIGATION OF SPRINKLER RESPONSE MODELS AND THE INTERACTION BETWEEN SPRINKLERS AND FIRE VENTS

This licentiate thesis includes the following reports:

[1] Ingason, H., *Thermal response models for glass bulb sprinklers* , SP-REPORT 1992:12, The Swedish National Testing and Research Institute, Borås 1992, Sweden.

[2] Ingason, H. and Olsson, S., *Interaction between sprinklers and fire vents*, SP-REPORT 1992:11, The Swedish National Testing and Research Institute, Borås 1992, Sweden.

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1 Introduction

The ability of sprinklers to suppress or control fires depends to a great extent on the rapidity with which they respond. Over the past decade, new sprinklers, such as Early Suppression Fast Response (ESFR) sprinklers for warehouse protection and residential sprinklers for use in residential occupancies, have been developed for which the requirement of **fast** response plays a key role. Thus, the ability to predict the response time of sprinklers in given fire situations has become increasingly more important. To predict the sprinkler response, knowlegde concerning the gas temperature and velocity at the ceiling, is required.

Semi-empirical relationships have been developed to predict the gas temperature and velocity at the ceiling for different fire conditions. Parameters such as fire size, fire growth rate and room geometry in two dimensions have been included. Heskestad and Delichatsios [1] published relationships with which the maximum temperature and velocity of fire gases can be predicted as they travel across the ceiling. The relationships assume a flat ceiling with no obstructions, and the ceiling jet is assumed to be radially axisymmetric. In many buildings these conditions are not fulfilled as obstructions and vents of different types are mounted in the ceiling. Local effects on the temperature and velocity fields caused by beams, smoke curtains, walls, fire vents or water spray from already activated sprinklers, can not be predicted with semi-empirical models. For these cases field model codes are required. Until now, there has been a lack of full-scale fire tests to verify simulations with field models codes. The experiments in [2] * provide the basis for the necessary verifications.

With the knowlegde of the ceiling jet temperature and velocity at any time and location, the response time of the sprinkler can be calculated. To predict the response time, a mathematical thermal response model for the sprinkler's heat-sensitive element is required. The thermal response model includes parameters which describe the heating characteristics of the heat-sensitive element. The thermal response parameters are determined from wind tunnel tests. In [1], an extensive investigation is described of different thermal response models to determine the most appropriate model for incorporation into the field model code JASMINE [2]. With an appropriate thermal response model the sprinkler response can be calculated for complicated cases such as when fire vents and beams are mounted in the ceiling. The interaction of sprinklers and fire vents has been discussed intensively during the last decade without any satisfactory solution. It may be possible to elucidate this question by using a field model code. However, an investigation of the ability of field models to predict local effects around a fire vent opening and the effects of the sprinkler water spray on the ceiling jet flow must first be undertaken. Therefore, as a first step in this direction, extensive experimental data for the verification of a field model code for such complicated cases are presented in [2]. If it is found that the field model calculations and the test results in [2] correlate well, then the field model codes can be used for more comprehensive studies of the local effects of fire vents, smoke curtains, ceiling slopes or beam constructions on the temperature and velocity field and the turbulence conditions at the ceiling.

* Numbers in brackets [2] refer to the report list on page 1 while superscripts [1] refer to the reference list.

2 Background

In the following, the background to the experimental and theoretical work in [1] and [2] is given.

2.1 The thermal response models

The heat-sensitive elements of sprinklers may have many forms but are basically of two types;

- metal linkages stabilized with soldered joints

- liquid-filled glass bulbs

As the heat-sensitive element heats up under fire conditions, the solder melts or the glass bulb shatters near a design temperature rating, usually about 70 °C. Only glass bulb type sprinklers were investigated in [1]. In Figure 1, one of the glass bulb type sprinklers used in the experiments, is shown from two sides.

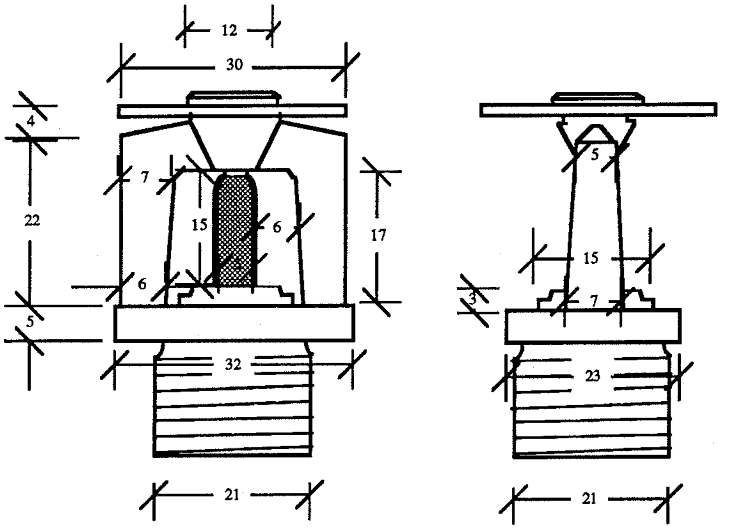

Figure 1 A glass bulb type sprinkler used in the experiments presented in [1]. The dimensions are given in mm.

There are several different response models available [3,5,6,7,12,15,16,17]. The thermal response parameters in these models are determined from wind tunnel tests under different heating conditions. There are two main types of wind tunnel tests in use today; the plunge test [3] and the ramp test [4]. In a plunge test, the sprinkler is "plunged" into the wind tunnel, in which the air stream is at a constant velocity and temperature. The time required for the sprinkler to activate is then recorded. In a ramp test the sprinkler is conditioned at a specific temperature and velocity before the test. The temperature in the wind tunnel is then increased linearly until the sprinkler activates. A schematic figure of the wind tunnel used in the experiments in [1], is shown in Figure 2. This wind tunnel has been used both for plunge and ramp tests.

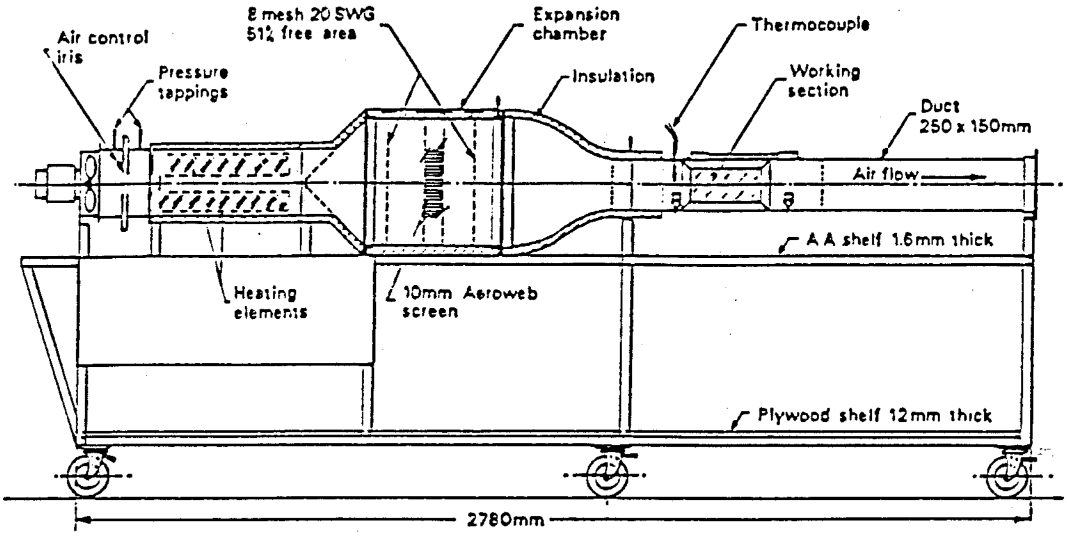

Figure 2 The wind tunnel used in the experiments presented in [1] was constructed in accordance with drawings from the Fire Ressearch Station in the UK.

In [1], an experimental and theoretical investigation of response models using one, two and three thermal response parameters, is presented. The thermal response parameters investigated were the Rate of Time Index (RTI) defined by Heskestad and Smith[3,5], the Conduction parameter (C), defined by Heskestad and Bill[6] and the Change of Phase parameter (CHP), defined by Gustafsson[7]. The RTI parameter is the product of the thermal time constant of the heat-sensitive element and the square root of the associated air velocity. The heat-sensitive element is assumed to respond to heating as a lumped heat capacity system, i.e. it is assumed to remain uniform in temperature. The C parameter includes the effects of heat losses from the heat-sensitive element to the sprinkler fitting. The CHP parameter was introduced to better explain test results which could not be fully simulated with only RTI and C parameters. Physically, the CHP parameter is assumed to be related either to an endothermic heat of fusion or to the work necessary to shatter the glass bulb shortly before activation. The RTI, C and CHP parameters can be determined from test data from ramp tests and plunge tests. In the mathematical response models studied, many simplifications and assumptions are introduced to make the models simple and practical in use. The assumptions introduced are discussed in Section 2.1.1.

As mentioned earlier, one of the main objectives of the work in [1], was to investigate the validity of some of the response models present available, especially the model using three parameters (RTI,C,CHP). The applicability of the one, two and three parameteter models for different fire growth rates were investigated to determine what response model should be introduced into the field model code JASMINE[2]. The experimental part consisted of wind tunnel tests with glass bulb sprinklers. The sprinklers tested had three different bulb diameters; 3, 5 and 12 mm. They were tested in a plunge test with three preheating temperatures and in a ramp test with two rates of temperature rise. The results of the investigation are discussed in Chapter 3.

2.1.1 Discussion of the assumptions introduced into the thermal response models

The original thermal response model for the description of sprinkler response was developed by Heskestad and Smith [3,5]. They introduced the RTI parameter to characterize the thermal sensitivity of the sprinkler. The basic assumptions were that

- the sensing element is heated purely by forced convection
- all heat transferred to the sensing element is stored there and there is no conduction loss to supporting structures
- the element heats isothermally, i.e. the temperature distribution in the heat-sensitive element is uniform (lumped heat capacity system)
- no additional heat is required to actuate the element, such as heat of fusion for solder type sprinklers.

The basic assumptions have been discussed by various authors during the last decade. The assumption of uniform temperature distribution in the heat-sensitive element during heating has been treated by Job et al. [8] They showed that the temperature gradients across the glass bulb would cause an initial delay in the temperature rise within the bulb and subsequently a delay in the response of the sprinkler. The consequence would be RTI values varying with heating conditions. In [1], a thermal analysis has been carried out to investigate the effects of temperature gradients on the response time and thus the RTI value calculated.

Pepi [9] questioned the constancy of the RTI value for all fire situations, and attributed the discrepancy in test results to conduction heat losses to the supporting structure. This observation led to the introduction of the conduction heat loss parameter C, by Heskestad and Bill [6]. The conduction parameter C, was assumed to be a constant value for each type of sprinkler. This parameter is today well established. There are two different methods of determining the C parameter, which may lead to different results. Heskestad and Bill [6] proposed a prolonged plunge test to determine the C value providing steady-state conditions for the heat-sensitive element at response of the sprinkler. The C value is then determined from a steady-state equation given by Heskestad and Bill [6]. Other methods used to determine the C parameter are based on the use of data collected directly from ramp or plunge tests and the necessary equations are solved explicitly.

Job et al.[8] concluded that the heat losses cannot be expected to be described by a constant C parameter, because the temperature increase in the frame follows a complicated function in a dynamic heating process which can cause considerably different temperature relations under different air flow conditions. The heat loss, from the heat-sensitive element, will be governed directly by the temperature difference between the heat-sensitive element and the sprinkler frame and indirectly by the water temperature at the sprinkler fitting. They concluded that the C parameter should therefore be determined under air flow conditions as similar as possible to those which could be expected in fire situations. An investigation of different combinations of ramp and plunge tests, on the constancy of the C parameter, is presented in [1].

The assumption that there is no heat of fusion has been investigated for solder links by Evans and Madrzykowski [10]. They concluded that the amount of energy associated with fusion of the link could be as much as 31 percent of the total energy transfer needed to rupture a link which was initially at room temperature. The conduction heat losses to the sprinkler fitting were not taken into account. This could easily have influenced their results. They did not investigate these effects for glass bulb sprinklers.

In earlier test series with glass bulb sprinklers [11], a discrepancy in the test results was attributed to heat of fusion or the work necessary to shatter the glass bulb shortly before activation (Gustafsson [7]). In the model, the CHP parameter was assumed to describe the delay of the sprinkler response shortly before activation. The reason for the suggestion was related to difficulties in explaining test results from the test series presented in reference [11], i. e. the FIRTO test series. The results could not be explained with a constant RTI parameter, nor did the addition of the C parameter explain the results. Thermal analysis using a computer program [12] which is based on the finite element method, has been performed to explain this phenomena.

No attempt has been made to explain the test results with the use of the approaches described in references [13,14,15].

2.1.2 Investigation of wind shadow effects

Job et al.[8] pointed out that the influence of the orientation of sprinkler frame arms relative to the direction of air flow should certainly be taken into consideration as some sprinklers might operate considerably slower in real fires than might be expected from response time tests at best positions in a wind tunnel. However, due to the artificially straightened air flow in wind tunnel tests, an overestimation of the shadow effects may arise compared with the real fire situation. Heskestad and Smith [3] state that in a real fire situation, a ceiling-mounted sprinkler would be exposed to a highly turbulent ceiling flow in which the instantaneous flow direction may vary over a wide angular range. The heat-sensitive element would be in the wake of the frame arms for only a small fraction of time during the heating interval. Consequently, the wind shadow effects, caused by the frame arms, are expected to be much less prounounced in the real fire situation than in wind tunnel tests.

When the sprinkler arms are orientated parallel to the direction of air flow it is not obvious that the Nusselt number should correlate to the square root of the Reynolds number, as it does when the frame arms are perpendicular to the air flow. One of the basic assumption in the RTI theory presented by Heskestad and Smith [3,5] is that the heat transfer to the heat-sensitive element correlates to the square root of the Reynolds number and thus the square root of the air flow velocity. The heat transfer to the glass bulb is proportional to the Nusselt number. When the sprinkler frame arms are orientated parallel to the air flow, the flow conditions around the glass bulb will change due to the shadowing effect of the frame arms. This will alter the convective heat flow to the glass bulb compared with the case in which the frame arms do not obstruct the flow. In [1], an investigation of the correlation between the Nusselt number and the Reynolds number for the glass bulb when the frame arms are orientated parallel to the air flow, is presented. The simulations were performed with a field model code.

In [1], the velocity field around the sprinkler, measured by Laser Doppler Velocimetry[16] (LDV), is shown. The objective was to measure the air flow conditions around the sprinkler frame arms at two different orientations. A field model simulation was carried out for same type of sprinkler to enable a comparision with the measured values.

2.2 Fire tests for verification of field model calculations

As mentioned earlier, it is important to be able to predict the response time of a sprinkler. There are conditions under which the response of the sprinkler are difficult to predict. The models available to calculate the velocity and temperature at the ceiling are correlated to experiments carried out under flat ceilings. In the Scandinavian countries most ceilings are not flat as they usually have extensive load bearing systems due to the high snow loads. The problems to be solved are therefore more often three-dimensional than two-dimensional and can only be simulated by more advanced methods such as field models.

Another example of the use of field models is the case in which automatic smoke ventilation is used in combination with sprinkler systems. The problems associated with automatic smoke ventilation in sprinkler-equipped buildings have been the subject of concern for a long time. There are several factors involved, the most important being the possibility that venting reduces the temperature beneath the ceiling and hence increases the response time of the sprinklers. To predict the effects of venting on the response of sprinklers, theories based on zone models, combined with semi-empirical relationships for the ceiling jet, have been published by Hinkley [17] and Cooper [18] among others. In the models, the fire vents are assumed to be evenly distributed over the ceiling so that the arrangement could be described as a "porous ceiling". No discrete vent openings are recognized and the temperature of the hot smoke layer is calculated as an average temperature. Local effects on the temperature and velocity caused by fire vents, smoke curtains or beams are ignored in these models. The ceiling jet is assumed to remain radially symmetric at all locations and the ceiling jet is modelled in the radial and the vertical directions. Depending on the geometrical shape and locations of the obstructions, the turbulence conditions in the ceiling jet can vary significantly from case to case. A sprinkler close to a fire vent or a beam is not subjected to the average temperature of the ceiling jet but the local temperature and velocity. The the ability of zone models to predict temperature and velocity in such cases has therefore been questioned[19].

During the past decade, the Swedish Fire Research Board (BRANDFORSK) has established a research programme, aimed at a better understanding of the phenomena involved. A natural step was therefore to initiate a project with the objective of investigating the validity of field modelling in the fire vent/sprinkler context, limited to the period before the activation of the first sprinkler. Specific activities have included the characterization of water sprays and the interaction between a water spray and a hot gas, performed at the South Bank Polytechnic by Gardiner [20] and Jackman [21].

A field model has many advantages compared with zone models, but there has been a lack of experimental data from large-scale experiments with which to verify the calculations. Therefore, large-scale experiments were carried out at the Swedish National Testing and Research Institute in a large test room, both with and without fire vents. The test room, measuring 7,5 m x 15 m and 6 m in height, is shown in Figure 3. The configuration of the test room (the walls correspond to very deep beams) and the location of the fire source and the fire vents were assumed to cover about 60 % of the possible combinations of the real cases for industrial buildings in Scandinavia [22]. The fire source was located at the centre of the test room and the position of the fire vent at the ceiling was varied. The fire vent in the ceiling had the dimension 1 x 2 m. Tests were also performed to investigate the influence of water spray on the ceiling jet. These test were performed to provide a basis for comparision between experiments and zone models such as Gardiner's [20] and field model calculations. Tests were also performed to investigate the influence of water spray on the outflow of hot gases through a fire vent. A number of tests were also carried out to estimate the influence of beams in the ceiling on the local velocity and temperature field.

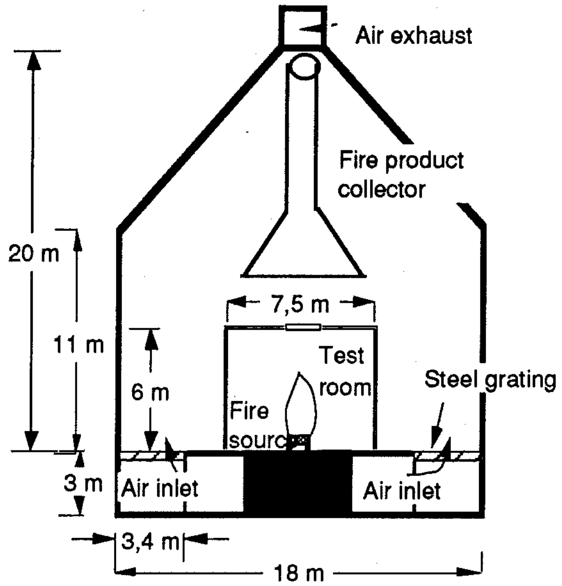

Figure 3 The test room used in the experiments was located in a larger test building at SPs Fire Laboratory. A section view of the test room and the test building is given with main dimensions.

The temperature and velocity fields were measured at different locations in the room and in the fire vent opening. Both growing and constant heat release rates were applied. The fire growth rates were in accordance with a power law relationship with a power value of two given by Heskestad and Delichatsios [1]. Three different fire growth rates were used; fast, medium and slow. In Figure 4 the layout of the instrument stations is given. The results of the experiments are given in [2].

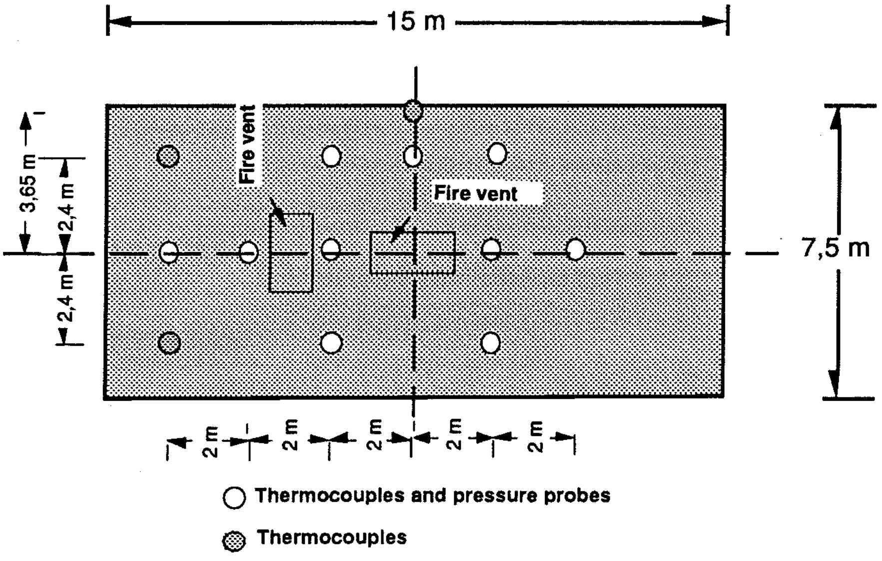

Figure 4 A plan view of the layout of the instrument stations used in the project.

3 Results

In the following, a summary of the results obtained in [1] and [2] is given.

3.1 The wind tunnel tests

Over 150 wind tunnel tests were performed with three types of glass bulb sprinklers. The sprinklers were delivered from the manufacturer as separate glass bulbs and sprinkler frames. A water cooling system was constructed to maintain the temperature at the sprinkler fitting relatively constant during the test. The water cooling system, consisted of a steel pipe assembly, plastic tubes, a small circulation pump (at the beginning of the test series the water was circulated by placing a bucket filled with water at a high elevation), a water reservoir and a heater to keep the water in the reservoir at a constant temperature. The water flow was maintained at 4 - 5 l/min. In one ramp test, with a rate of temperature rise of 2 °C/min, the water temperature at the sprinkler fitting was measured with a 0.25 mm thermocouple and was found to increase by about 4 °C during the test. The gas temperature at this point was about 97 °C.

The sprinklers were tested in a plunge test with three preheating temperatures and in a ramp test with two rates of temperature rise. Each sprinkler was tested at two orientations, with the frame arms perpendicular and parallel to the air flow. Based on these test results, the thermal response parameters, RTI, C and CHP, were determined.

3.1.1 Prediction of wind tunnel tests

The applicability of the response models was investigated by predicting response times in tests performed under other conditions than those used to determine the thermal response parameters. By increasing the number of thermal response parameters, a better correlation between prediction and observation can be expected. In Figure 5, results are shown for the 3 mm glass bulb sprinkler, using two parameters (RTI+C; two-parameter model) and three parameters (RTI+C+CHP; three-parameter model).

In [1], corresponding graphs can be found for the two other sprinkler types and for the ramp test. The graph in Figure 5 shows that the three-parameter model gives improved predictions of the response time and a reduced spread in the results compared to the two-parameter model. These findings were in accordance with the results obtained earlier by Gustafsson [7] when he analysed the test results from the FIRTO [11] test series. In [1] it was shown that the discrepancy between the predicted and measured response times, when using the two-parameter model, is related to parameters determined from tests with a high preconditioning temperature(52 °C). One could expect that this behaviour is related to some physical phenomenon occurring at high preconditioning temperature and therefore it is motivated to use three parameters as Gustafsson has proposed [7]. In [1] it was found that this

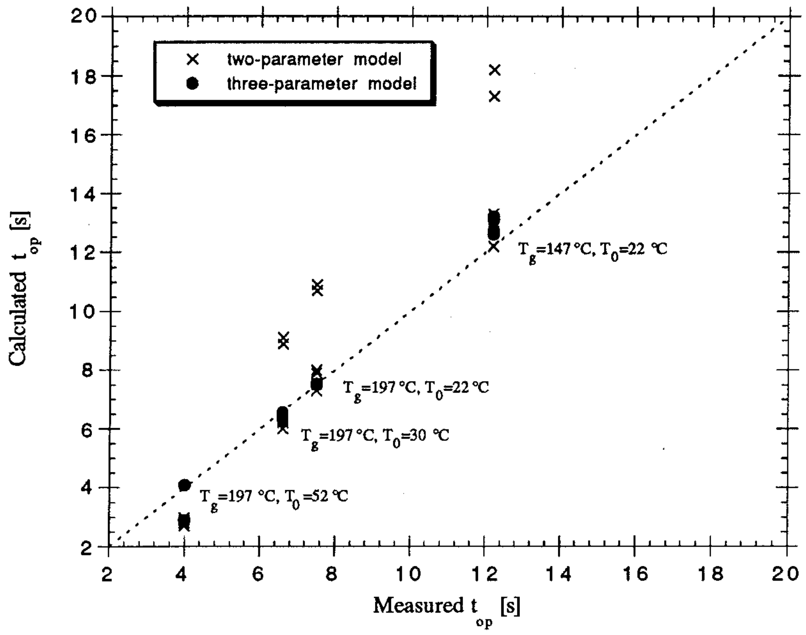

Figure 5 Calculated versus measured response time for a Ø 3 mm sprinkler in plunge tests under different test conditions. Both two- and three-parameter models were used.

behavior could be related to the time delay caused by the temperature gradients created across the glass bulb. A time delay due to endothermic phase change or work needed to shatter the bulb just before activation is therefore not likely. The bulb simply brokes due to the internal pressure created by the average temperature of the liquid. As the thermal response model assumes no temperature gradients in the glass bulb, a time difference will appear between simulated and measured response times. These effects are especially large at high preconditioning temperatures of the glass bulb.

3.1.2 Results of calculated response times for real fire conditions

The response models have also been evaluated for realistic fire conditions. A fire growth rate following a power law correlation [1] as the square of time was used. According to Heskestad and Bill [6], the heat release rate (HRR) at response of a sprinkler for growing fires, is a more meaningful measure of a sprinkler responsiveness than the response time. Therefore, the thermal response parameters determined from the different test conditions, have been used to calculate the HRR value at sprinkler response.

The calculations were carried out for the tested sprinklers at two ceiling heights; 3 m and 6 m, respectively. The ambient temperature of the sprinkler was T_0=22 °C, and the radial distance from the fire axis was 2.12 m. The results are presented graphically in [1] (see Figure 6) in the form of a normalized HRR. Calculations of HRR at sprinkler response with one-, two- and three-parameter models, are given in the graph where the HRR values have been normalized to the lowest HRR value, obtained from a calculation with one parameter, RTI, for the same sprinkler type and ceiling height. In all the cases, the slow fire growth rate gave the lowest value (indicated by x in Figure 6). Figure 6 demonstrate the effects of using two or three parameters in the response model compared with the use of one parameter. For HRR values calculated with the two- and three-parameter models, distinction is made between calculations with parameters determined from ramp tests with rate of temperature rise 10 °C/min and 2 °C/min, respectively. This is done in order to clarify the effects of different rates of temperature rise, ß, on the calculated HRR value at sprinkler response.

Higher C values were obtained with ramp tests based on ß=10 °C/min than from tests with ß=2 °C/min. This is reflected in the Figure 6 because higher HRR values at sprinkler response are obtained with parameters determined from ramp tests with ß=10 °C/min than from tests with ß=2 °C/min. Corresponding graphs for 5 and 12 mm glass bulb sprinklers can be found in [1].

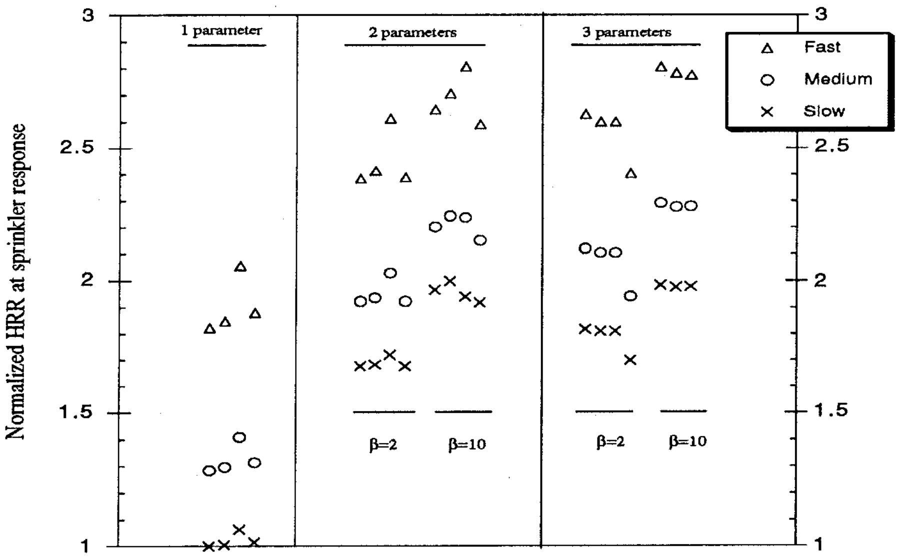

Figure 6 Normalized HRR at sprinkler response of a Ø 3 mm sprinkler at a height of 3 m. The lowest HRR value obtained was used to normalize the other values. Distinction is made between calculations with parameters determined from ramp tests with ß=10 °C/min and ß=2 °C/min, respectively.

The following conclusions were drawn from the graphs in [1]:

- Relatively small changes in the calculated HRR at sprinkler response are observed between the three-parameter model and the two-parameter model.
- The spread in the results is reduced when three parameters are used instead of two, but the difference in calculated HRR values is small. Thus, the three-parameter model is questionable from a practical point of view.
- The effect of C is quite large at low RTI and less significant at higher values of RTI. This is the same conlusion as Heskestad and Bill [6] obtained in their sensitivity analysis of the one- and two-parameter model.

- Overall, the difference between the normalized HRR values at sprinkler response for the different fire growth rates, increase with higher RTI values (larger bulb diameters) and decrease with the clearance height between sprinkler and fire source.

3.1.3 Thermal analysis carried out with the finite element method

To investigate the discrepancies revealed in Section 2.1.1, a thermal analysis using computer simulation was carried out. The following assumptions made in earlier studies [3, 5, 6] were investigated more closely:

- the heat-sensitive element (the glass bulb in this case) heats isothermally (time delay due to temperature gradients is therefore neglected)
- the sprinkler fitting is essentially at ambient temperature and the conductive heat loss rate is proportional to the temperature difference between the heat-sensitive element and the sprinkler fitting.

Both these assumptions were investigated for glass bulbs through an analysis with the Finite Element Method (FEM) [23]. The program used is named SUPER-TASEF [24]. In Figure 7 the 5 mm sprinkler and dimensions of an idealized glass bulb used in the simulation are shown.

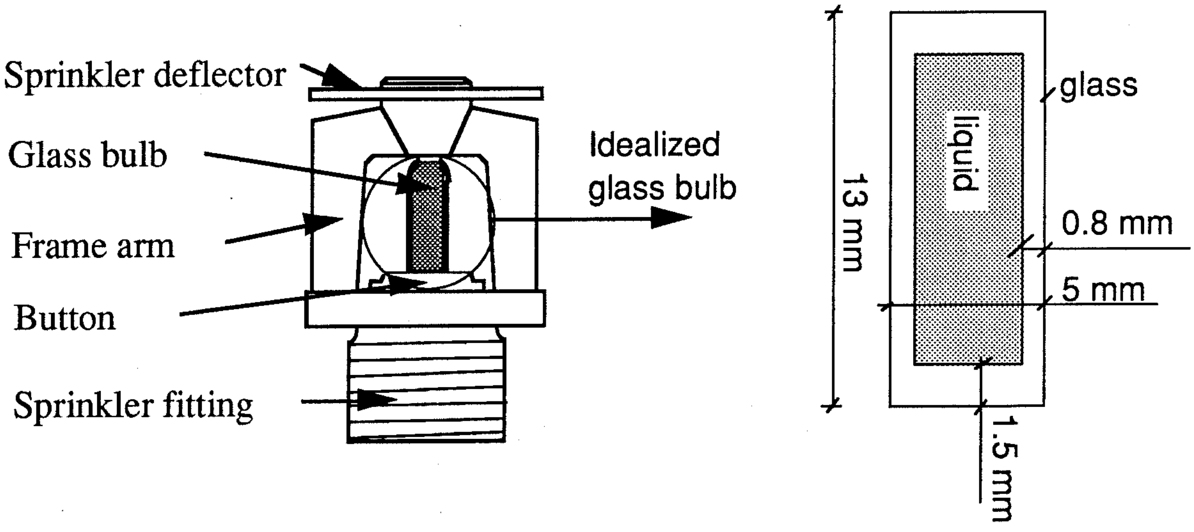

Figure 7 The Ø 5 mm sprinkler used in the test series. The shape of the glass bulb is simplified to a rectangular form to facilitate the calculations.

The computer simulation of the test results was carried out with the 5 mm sprinkler bulb. It was assumed that pure heat conduction is the only heat transfer mechanism in the liquid. It can be shown that this is a realistic assumption by estimating the Grashof number (Gr) for free convection within the glass bulb. At very low Grashof numbers, there are very minute free-convection currents and the heat transfer occurs mainly by conduction across the fluid layer [25]. Calculations in [1], show it is realistic to assume that the heat transfer in the glass bulb can be simulated by pure heat conduction.

The glass bulb was assumed to be heated by forced convection and cooled by heat losses to the sprinkler frame. The heat transfer coefficient was calculated according to an equation for free flow around a cylinder. The heat loss coefficient at the ends of the glass bulb, was determined by fitting the calculated response time to the measured response time in a ramp test with ß=2 °C/min. The correspondence between the calculated response time and the measured response time was very good for the simulated plunge tests. In Figure 8 the results are plotted.

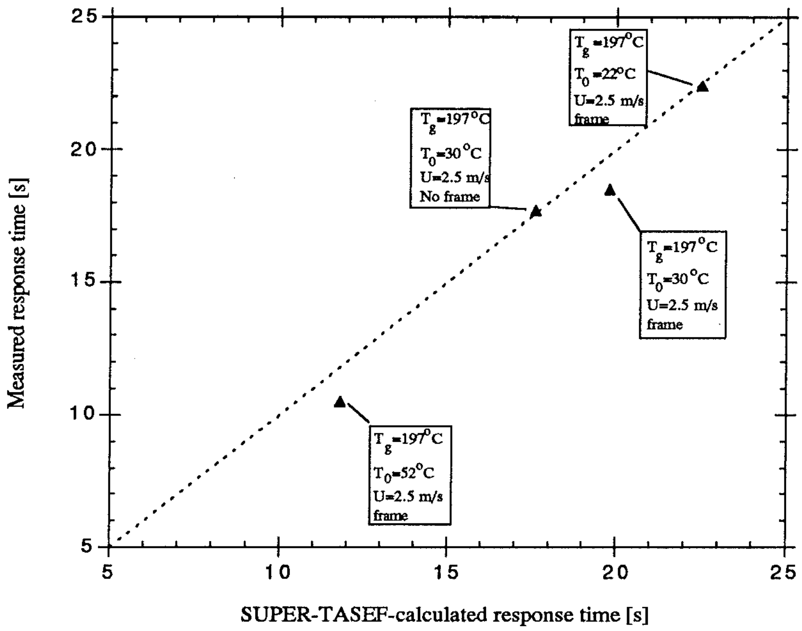

Figure 8 The measured response time versus calcualted response time with SUPER-TASEF in different plunge test situations.

As mentioned earlier, it was observed that the value of the parameter C was higher when determined from ramp tests with ß=10 °C/min, than ramp tests with ß=2 °C/min. The same tendency was observed in the results obtained from the calculations with the finite element program. The value of the heat loss coefficient at the ends of the bulb (for ß=10 °C/min) must be higher than than the value obtained as best fit to the response time with ß=2 °C/min. Measurements and calculations show that this might be attributed to an uneven heating of the frame during the ramp tests.

The effects of temperature gradients on the calculated RTI values were explained by calculations with the computer program SUPER-TASEF. The reason for the higher RTI value for a high preconditioning temperature is more likely to be caused by different effects of the time delay (related to the temperature gradients) rather than heat of fusion or a work required to shatter the bulb shortly before activation. This can explain the difficulties in obtaining agreement between predicted and observed response times using the two-parameter model when response times based on tests with high preconditioning temperature were used to calculate the RTI and C parameters. It is shown in [1] that the relative effects of the time delay increase with more severe plunge test situations (shorter response times) subsequently leading to higher RTI values. This means that increasing gas temperature and increasing gas velocity will increase the RTI value for a certain glass bulb.

In Figure 9 the temperature contours and the heat flux vectors under plunge test conditions with heat losses to the sprinkler fitting is shown. The temperature gradients across the glass bulb and the heat flow distribution within a glass bulb can be seen in this figure.

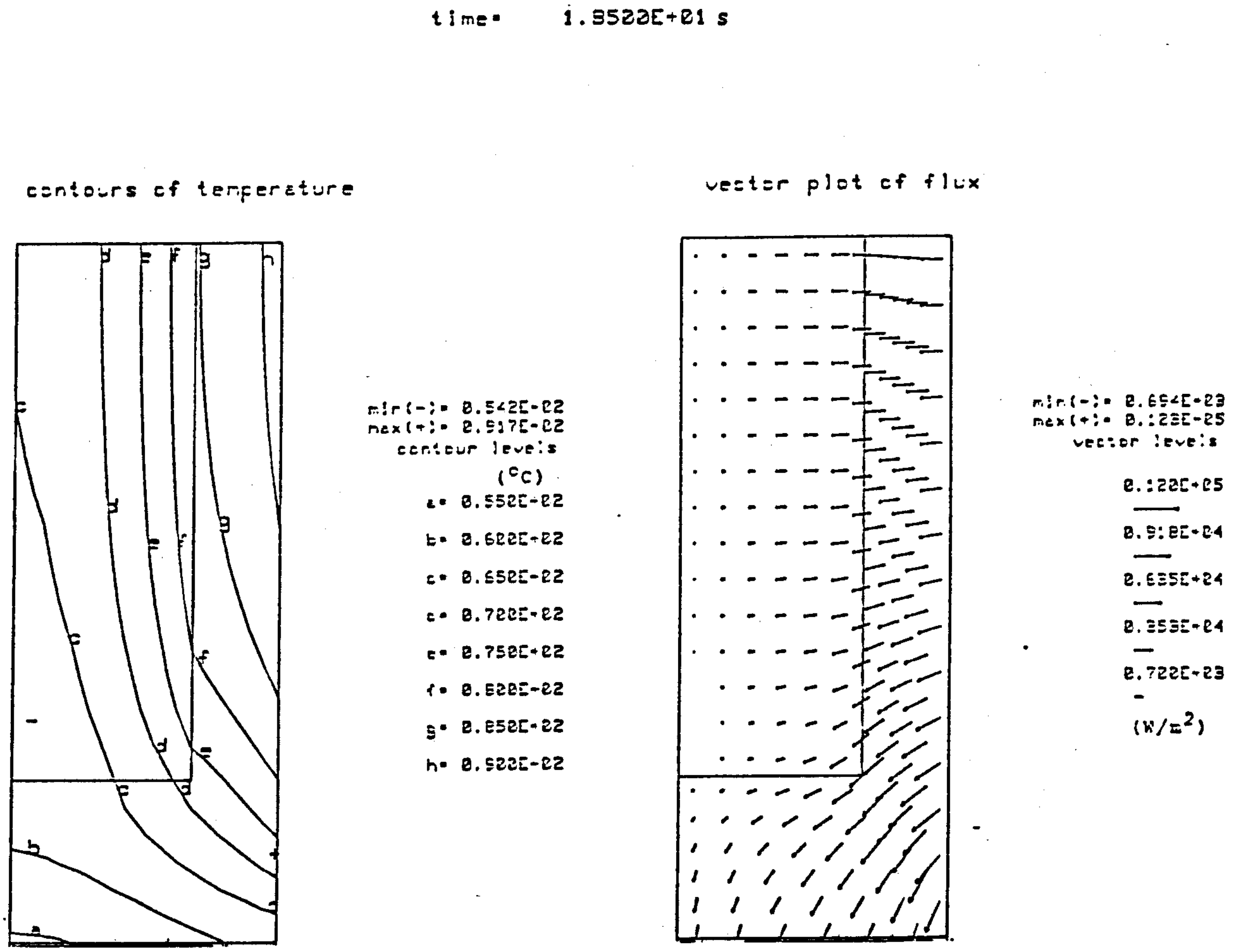

Figure 9 Temperature contours and heat flux vectors under plunge test conditions with heat losses to the sprinkler fitting. Tg=197, Tl=30 °C, u=2.5 m/s. A quarter of the glass bulb is shown.

A theoretical investigation of the effects of radiation on the response time was carried out using SUPER-TASEF. The 5 mm glass bulb was used in the analysis. The wall temperatures had been measured during the tests and they were used as input for the calculations. The calculations showed that the radiation effects are more significant in a ramp test than in a plunge test, but the effects on the calculated response time, in real fire conditions, are small. The systematic error caused by the effects of radiation exchange in a wind tunnel test will therefore have minor effects on the calculated response times in real fire conditions.

3.1.4 Theoretical analysis of the wind shadow effects

A theoretical analysis of the wind shadow effect caused by sprinkler frame arms has been performed. The results were compared with the LDV measurements. A more comprehensive analysis is given by Ingason and Persson [26]. The flow around the glass bulb and the frame arms was simulated using a finite volume computer code named FLOPAC [27].

When the sprinkler frame arms are orientated parallel to the air flow, the flow conditions around the glass bulb will be different compared to the case in which the frame arms are orientated perpendicular to the flow. An investigation of the Reynolds number dependence of the heat transfer to the glass bulb has been carried out for both orientations. The RTI theory for sprinkler response assumes that the heat transfer to the glass bulb is proportional to the square root of the Reynolds number. The objective of the simulation with FLOPAC was to investigate whether the Reynolds number dependence is the same irrespective of the orientation of the sprinkler.

Calculations have been performed assuming an inlet temperature of T_i=200 °C, a bulb wall temperature of T_w=20 °C, and for the following free stream velocities ahead of the sprinkler:

α=0° : U=1, 1.5, 2, 2.5 and 5 m/s
α= 90° : U= 1, 2.5 and 5 m/s

Here α denotes the orientation of the sprinkler, α=0 denotes the "best" case when the sprinkler frame arms are aligned with the flow. The case α=90° denotes the "worst" orientation i.e. when the flow is perpendicular to the frame arms.

Figure 10 shows the Nusselt number as a function of the Reynolds number for the best and the worst orientations. The Nusselt number in Figure 10 is given as a mean value around the perimeter of the glass bulb. In reality, the Nusselt number, and thus the heat transfer coefficient, varies around the perimeter.

As can be seen from Figure 10, the Nusselt number and, thus the convective heat transfer, is more than halved compared with the case when the frame arms are aligned with the flow. This will result in more than a doubling of the response time for the sprinkler. This result is in good agreement with the results of experiments performed for the 5 mm sprinkler.

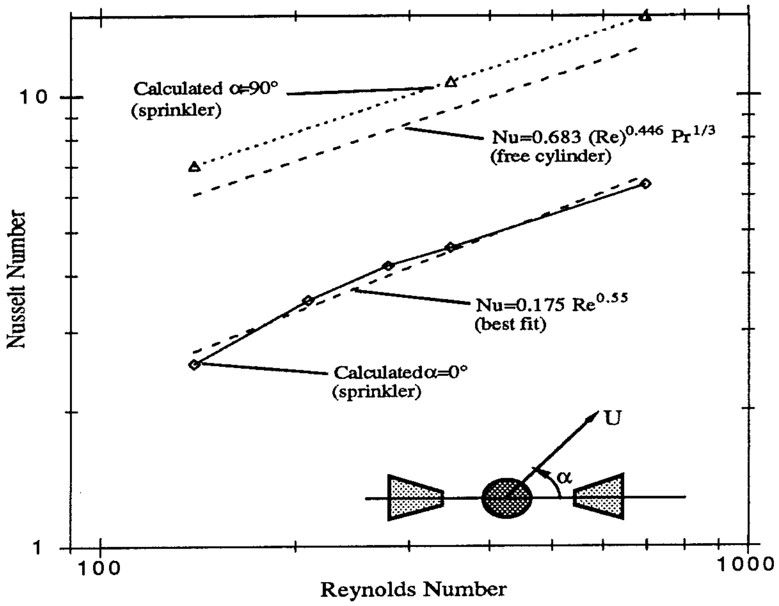

Figure 10 Calculated Nusselt number as a function of Reynolds number for best and worst orientation of the sprinkler (Pr = 0.7).

The following correlation for the Nusselt number was found to give the best fit for the 5 mm sprinkler with the frame arms parallel to the air flow.

$$\mathrm{Nu} = 0.175\,\mathrm{Re}^{0.55} \tag{1}$$

The Reynolds number dependence of the heat transfer coefficient is therefore approximately the same for both orientations. This means that the foundation of the simplified theory for sprinkler response, assuming the heat transfer to be proportional to the square root of the Reynolds number, is valid irrespective of the sprinkler orientation. Thus, by using the same free stream velocity for all orientations in determining the response time, different RTI values will be obtained. This is, of course, an unfavorable situation as one should prefer the RTI value to be a constant for each specific sprinkler type.

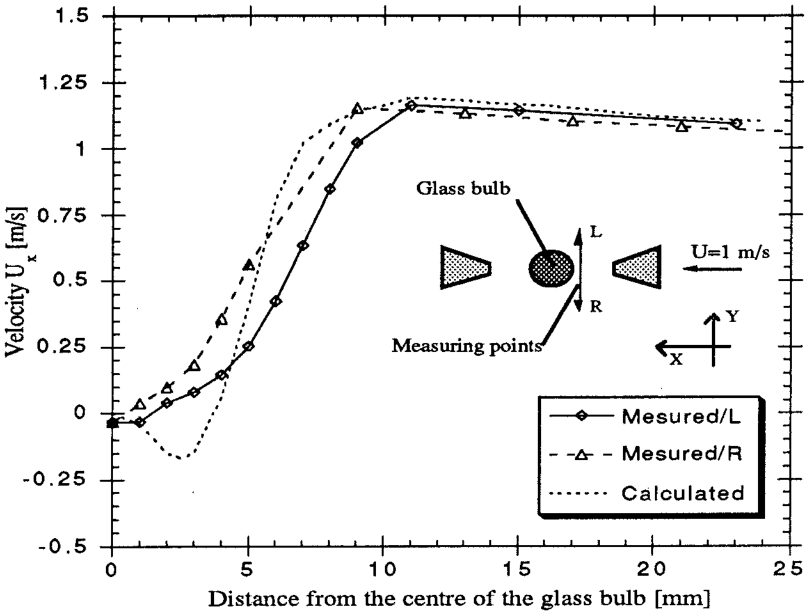

Figure 11 Comparison between the computed Ux velocity profile with FLOPAC and the experimentally determined profile using LDV for the worst orientation. The measurements were performed sidways to the air stream between the glass bulb and the upstream frame arm. L and R denotes values on different sides of the glass bulb. The free stream velocity U was 1 m/s.

Figure 11 shows a comparison between the computed velocity profile and the experimentally determined profile using LDV for the worst orientation. As can be seen the agreement is very good except for the region close to the bulb. The negative velocity in this region is due to the separated flow from the frame arm.

3.2 The full scale test with sprinkler and fire vent

The test programme described in [2] was divided into four major parts :

- test series with different fire growth rates and fire vent conditions to investigate local effects of the fire vent on the temperature and velocity field.

- investigate the influence of water spray, discharged from a conventinal sprinkler, on the ceiling jet.

- investigate the effects of water spray on the outflow of hot gases through a fire vent by varying the location of the sprinkler.

- investigate the influence of beam constructions located in the ceiling on the velocity and temperature fields.

3.2.1 Tests with different fire growth and vent conditions

In the first part, tests were carried out under different fire vent conditions and fire growth rates. Due to the configuration of the test room no hot gas layer was able to build up and the gas flow in the ceiling was therefore dominated by a horizontal momentum flow.

The maximum heat release rate from the growing fires was 1.5 MW resulting in temperatures at the ceiling from 50°C to 130 °C, depending on the distance from the fire source, and velocity values from 1 to 4 m/s. The thickness of the ceiling jet was approximately 1 m and the thickness of the temperature profiles was in good agreement with the size of the velocity profiles. Tests with constant rate of heat release at 1.2 MW were also performed.

The fire vents applied clearly affected the temperature and velocity field in the test room. The temperature reductions varied depending on distance from the fire vent. The observed effects on the temperature and velocity fields are probably out of range for zone models, but possible to predict with field models. In Figure 12 temperatures at an instrument station located 3 m from the fire source and 1 m downstream from the eccentric vent are shown for different vent conditions in the ceiling.

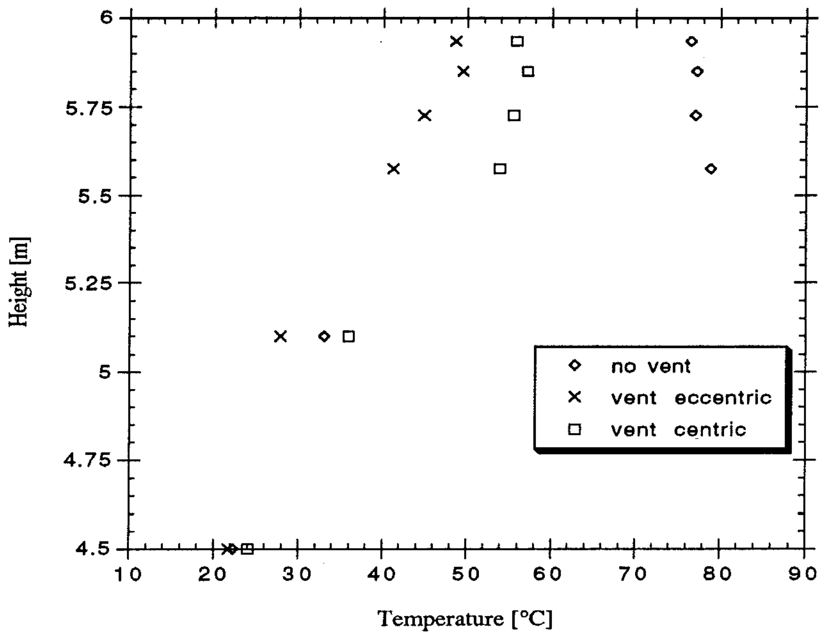

Figure 12 Temperatures at an instrument station 3 m from the fire source are shown for different vent conditions in the ceiling for the fast fire growth rate after 3 minutes. The instrument station is located 1 m downstream the eccentric vent (see Figure 4). The height is given from floor level.

In [28] comparision is made between the results obtained in the experiments and with the two zone model LAVENT [18]. The correlation was not good as the massflow out of the fire vent was equal to zero for the all cases. The program assume that a hot smoke layer will be build up but this was not the case in the experiments. In the experiments there was a great difference in the temperature and velocity field at the ceiling depending on the location of the fire vent i.e. centric or eccentric. The program LAVENT can not distinguish between these cases.

Experiments with sprinklers mounted at the ceiling demonstrated the effects of the when the fire vent was located above the fire source. With the fire vent mounted eccentric to the fire source it was not clear if the fire vent had any impact on sprinklers located upstream from the fire vent. From temperature and velocity data it could be observed that the fire vent clearly reduced the temperature and velocity field downstream from the fire vent. Measurements of total heat release rate through the fire vent show that the efficiency of the fire vent varied depending on the location of the fire source in relation to the fire vent.

3.2.2 Impact of sprinkler spray on the ceiling jet

The impact of sprinkler spray on the ceiling jet was investigated by applying a conventional sprinkler mounted in a pendent position at the centre of the test room. The fire source was moved to one end of the test room and a terminal wall was attached to the ceiling to force the hot gases in one direction.

As could be expected, the water flow rate influenced the cooling of the ceiling jet. At centreline instrument stations downstream from the sprinkler spray, the temperature reduction depended on the water flow rate. For example; the temperature 150 mm below the ceiling could decrease from 90°C to 78°C at 80 l/min and from 90°C to 70°C at 100 l/min. The temperatures were slightly influenced at instrument stations downstream from the sprinkler and 2.4 m from the centreline. The temperatures upstream of the sprinkler spray tended to increase in some cases and decrease in others. Some kind of 3-dimensional blocking effects are probably the reason for this but the results were not very conclusive.

The velocities of the ceiling jet were slightly reduced downstream from the sprinkler spray. At corresponding measuring points to those for the temperature example above, the velocity was reduced from 1.9 m/s to 1.7 m/s at 80 l/min and from 1.9 m/s to 1.5 m/s at 100 l/min. The effects of the distance between sprinkler deflector and the ceiling on the temperature and velocity fields are not clear from the results. Further analysis is required.

3.2.3 Influence of the sprinkler location on gas flow through a fire vent

One of the objectives of the project was to investigate how a sprinkler spray, located at various distances from the fire vent, influences the gas flow out through the fire vent. This was investigated by locating a fire source at the end of the test room and moving the sprinkler in relation to the fire vent. The fire vent was mounted in the centre of the test room.

The results show that if the sprinkler is located upstream of the fire vent, it will have a significant impact on the gas flow. The experiments also demonstrated the influence of the sprinkler distance from the fire vent and the water flow rate on the gas flow. With the sprinkler located downstream from the fire vent the influence on the gas flow was negligible. It is clear from these results that the location of the sprinkler affects the gas flow through the fire vent. The impact on the gas flow is greatest when the sprinkler is very close to the fire vent and decreases with the distance.

3.2.4 Influence of beam constructions in the ceiling

A beam construction was mounted in the ceiling to investigate the impact on velocity and temperature fields. Two 0.5 m high beams were mounted in the ceiling and the fire source was placed between the beams at floor level.

The results show that the beam construction influenced the temperature and velocity field considerably. In the space between the two beams the increase in both temperature and velocity would definitely influence the sprinkler operation. In the spaces between the walls and the beams the velocity and temperature were reduced and the velocity was influenced more than the temperature. The thickness of the ceiling jet was not significantly affected.

4 Conclusions

The main conclusions in [1] are:

1) The test results can not be fully explained within the framework of the thermal response models applied.

2) The C parameter was found not to be constant for different rates of temperature rise in ramp tests.

3) Tests with a preconditioning temperature close to the operation temperature resulted in higher RTI values than in cases with normal preconditioning temperatures. This is probably more related to the effect of a time delay, which is caused by a non-uniform temperature distribution, rather than heat of fusion or work necessary to shatter the bulb, as proposed by Gustafsson [7].

4) The difference in the calculated response times when using two- and three-parameter models in real fire conditions was small. The gain in using three parameters (RTI+C+CHP) instead of two (RTI+C) is therefore insignificant in practice.

5) The cooling of the sprinkler fitting must be standardized accurately otherwise the heating of the sprinkler frame will vary considerably .

6) Field model calculations of the wind shadow effects showed that the heat transfer to the glass bulb in a sprinkler with the frame arms orientated parallel to the air flow, also correlated to the square root of the free air flow velocity.

7) The good agreement obtained between the measured and calculated velocity field around the sprinkler frame and the measured and calculated temperature development inside the glass bulb, shows that the finite element and the field model techniques are excellent tools for further research in sprinkler development, both for glass bulb and solder link sprinklers. Improvements and optimization of sprinkler design constitute a field which could benefit from these techniques.

8) It is concluded that further work is needed to

   - investigate the constancy of the parameter C in a real fire situation.

   - model the effects of the time delay caused by the temperature gradients within a glass bulb.

   - perform further calculations to ascertain whether the conclusions of the convective heat transfer to the sprinkler bulb with the frame arms parallel to the air flow varies with the square root of the velocity for other types of sprinklers as well. Experiments concerning the wind shadow effects in real fire situations are preferable.

The main conclusions in [2] are:

1) There is a possibility that venting reduces the temperature beneath the ceiling and hence increases the time to activation of the sprinklers. The observed effects on the temperature and velocity fields were generally of such a nature, that they are probably out of the range of zone models, but may be predicted with field models.

2) The water flow rate of the sprinkler influences the cooling of the ceiling jet at the centreline downstream from the sprinkler spray. The temperatures were slightly influenced downstream from the sprinkler and 2.4 m from the centreline. The temperatures upstream of the sprinkler spray tended to increase in some cases and decrease in others. Some kind of 3-dimensional blocking effects are probably the reason for this but the results were not very conclusive. Simulation of the cooling effects on the ceiling jet in three dimensions is only possible with field models.

3) If the sprinkler is located relatively close to the fire vent and upstream of the vent, the sprinkler spray will have a significant impact on the gas flow out of the fire vent.

4) Beams in the ceiling influence the temperature and velocity field considerably.

5) To complete this work, a comparision between the calculated and measured temperatures and velocities, is necessary. By introducing the two-parameter model (the influence of the temperature gradients in the glass bub is neglected as no mathematical response model for that exists at this time) in JASMINE for calculation of the response time, the field model code can be used for more comprehensive studies of the local effects of fire vents, smoke curtains, ceiling slopes or beam constructions on the temperature and velocity field together with the turbulence conditions at the ceiling.

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