Validation of CFD calculations of full scale medium sized fires in a two lane road tunnel

D J den Boer, J J Mertens, N J van Oerle
Peutz bv, The Netherlands
J F Wijnia
Peutz bv, UK

SYNOPSIS

In November 2001 a new road tunnel in The Netherlands was abandoned for two months to be able to carry out 25 full-scale fire tests in commission of the Dutch Ministry of Transport, Public Works and Water Management. The conditions in the tunnel were measured during several types of fires including car fires, lorry fires and pool fires. Also the impact of longitudinal ventilation on the conditions in the tunnel was examined. CFD calculations of some of the tests were carried out using the CFD code PHOENICS. The extensive temperature measurements performed during the experiments provided the opportunity to validate these CFD calculations. The results of this validation are presented in this article where is shown that qualitative and quantitative accuracy of the calculations performed is reasonable with respect to the uncertainty in the development of real fires in tunnels. Overall phenomena like the occurrence of backlayering and stratification are predicted. The backlayering lengths are under-predicted and the thickness of the smoke layer is over-predicted for which several causes can be pointed out. It is shown that CFD calculations can be used as a predictive tool in the design of the tunnels and tunnel installations. The use of this tool is economic and does not come with the risks involved with in situ full-scale fire test.

1 INTRODUCTION

CFD calculations are used more and more as a tool in predicting the conditions in tunnels during fires and evaluating the effect of safety measures, e.g. ventilation, on these conditions [5, 6, 7]. It is of great importance that the reliability of these calculations is addressed in detail. A limited number of full-scale experiments are available and suitable for the validation of CFD calculations. The Dutch Ministry of Transport, Public Works and Water Management initiated a series of experiments in a newly built underwater tunnel that were carried out by others. The measurement data as well as a detailed description of the experimental configuration [1] were made public which provided the opportunity to use this data for the validation of CFD calculations. This tunnel, the 2nd Beneluxtunnel, is one of the connections between the north and south coast of the 'Nieuwe Maas' in Rotterdam. The tunnel has 6 tubes: two double lane road traffic tubes, one single lane road traffic tube, one pedestrian tube, and two single lane underground (metro) tubes. A schematic presentation of the cross section is shown in figure 1. The experiments were performed in one of the double lane, road traffic tubes in the winter of 2001-2002. Fire tests using cars, lorry models, wood stacks and liquid fuels (n-heptane-toluene mixture) were carried out. During the tests extensive measurements of the temperatures were made. Limited measurements of the velocities, smoke densities and radiative fluxes were executed by the test contractors. Although several goals were formulated, some of the experiments provided a good opportunity for validation of CFD calculations.

2 TUNNEL AND EXPERIMENTAL SETUP

The tunnel used in the experiments is an underwater tunnel with a total length of 900 m. The ramp of the tunnel in the measurement area is 4.4 %. The dimensions of the cross section are 9.8 m x 5.1 m (width x height). The fire site was located at 260 m from the northern portal. Over a length of about 50 m upstream and 35 m downstream from the fire the concrete tunnel walls were protected. The tunnel roof was protected over the complete length of the tunnel. Two sea containers (6x2.44x2.59 mxmxm) were placed up- and downstream of the fire in order to simulate the presence of traffic. Temperature measurements were performed at 10 and 20 m upstream and at 10, 20, 50, 100 and 200 m downstream of the fire. For each of these positions the temperatures were measured at 5 heights (1.5, 3.0, 4.0, 4.5 and 5.0 m). A schematic overview of the fire area is shown in figure 2. Only jet fans upstream of the fire were present in the tunnel to avoid damage of fans during the tests. Since limited measurements of the velocities were made, the main emphasis of the article is in the comparison of measured and calculated temperatures.

3 CFD MODEL

The calculations are carried out with the general purpose CFD code PHOENICS V 3.3 [3]. Standard components for the modelling of turbulence, heat transfer etc. are available in the code. The calculations are performed using the ideal gas law, accounting for radiative heat transfer and without a combustion model. All calculations are transient calculations. In the following a brief overview of the models used is presented.

Turbulence

Turbulence is modelled using the (standard) k-ε model, corrected for the buoyancy effect on turbulence.

Walls

The temperature fields in the walls are solved during the calculations accounting for the different materials (concrete and protective measures). The properties of the materials used in the tunnel are assumed to be temperature and time (no evaporation of water) independent. Convective heat and momentum transfer to the walls is calculated using standard wall functions.

Fire

The combustion process is not simulated in detail. The fire is represented as a volumetric source of heat and smoke. The volume of the fire is estimated in advance on the basis of basic flame length relations [4] and kept constant during the calculations (flame height about 3 m).

Smoke
Smoke is represented with a scalar representing the local optical density. No corrections are made for the change of the thermodynamic properties of the gas with changing composition due to the combustion process (production of CO_2, H_2O etc.). The variation of the heat capacity of the gas with temperature is described with a first order relation. The smoke production (mass optical density) was determined on the basis of small-scale experiments and is assumed to be proportional to the RHR [1].

Radiation
Radiation is modelled using the composite radiosity model. A local, grey gas absorption coefficient is calculated from the local optical density. Because the absorption process of radiation is more effective with rising smoke temperature (assuming grey gas behaviour), a linear relation of the absorption coefficient with temperature was adopted.

About 30-35 % of the heat released is modelled as a direct source of radiation in the fire volume. Radiative heat transfer between fire, smoke layer and walls is calculated in detail.

Tunnel and ventilation system
The first 350 m from the portal of the tunnel is modelled including the grade of this part of the tunnel. The remaining part of the tunnel is accounted for by the boundary conditions of the model. Fans are not modelled in detail. When the fans were operated in the experiment (all upstream of the fire) the measured velocities 50 m upstream of the fire were used as boundary conditions for the model, assuming a uniform velocity profile.

The tunnel is curved slightly in the horizontal plane. No significant effect was expected from this, therefore this aspect was not modelled.

Mesh
A non-regular structured Cartesian mesh is used in the calculations (figure 9). About 110.000 cells were used for the fluid region of the model. The mesh is denser in the fire region.

4 EXPERIMENTS

A series of 25 tests were performed during the program. A selection of the most suitable experiments was used for the calculations. In the selected experiments the sprinkler system was not activated and liquids or pallets were used as a fuel. The rate of heat release (RHR) for these tests could be determined more accurate then for the tests with cars. Calculations were carried out for three pool fires and one pallet fire. An overview of these experiments is presented in table 1.

Table 1 Overview experiments

Experiment	Heat source	Mechanical ventilation (jet fans)	Maximum RHR [MW]
1	n-Heptane-Toluene mixture	No	4 MW
3A	n-Heptane-Toluene mixture	No	15 MW
4	n-Heptane-Toluene mixture	Variable (1-6 m/s)	15 MW
8	Pallets (wood)	No	13.5 MW

The RHR of the fires was not measured directly. The RHR of the pool fires used in the calculations is based on the measured flow of the fuel to the fire area. The RHR was calculated using an effective heat of combustion (38 MJ.kg^{-1}). In test 3A the temperatures 10 m and 20 m downstream showed a strong and unexpected increase of temperature during the first 10 minutes. On the basis of these temperatures the estimated development of the RHR was corrected leaving the total amount of heat released during the test unchanged.

During the pallet fire (test 8) the weight of the stacks was measured. The resulting RHR was calculated assuming an effective heat of combustion of 13 MJ.kg^{-1}. In this fire a few tires were added to the stack in order to generate enough smoke. Also a synthetic hood was present in order to simulate a lorry. The RHR was not corrected for the use of these materials. The RHR's used in the calculations are presented in figure 3. In test 4 the ventilation system was activated. At 50 m upstream of the fire velocity measurements were carried out. These values (figure 4) were used as boundary condition for the CFD model. As can be seen in the figure the ventilation velocity gradually increased during the test.

5 RESULTS

Temperature profiles

The measured and calculated temperature profiles of the selected experiments are presented in figure 5a, b, c and d. The measured and simulated temperature profiles in the middle of the tunnel at several distances from the fire are shown in the figures presenting the fully developed phase of the fires. In general the CFD calculations tend to over-predict the thickness of the smoke layer. As a consequence of this the stratification was under-predicted. The accuracy of the calculated flow can be deduced from figure 6 where the measured and calculated flows of test 3A are presented (velocity measurements at 2.5 m height 50 m upstream of the fire). The calculated flow was over-predicted by about 20 % (since all velocity measurements were performed at one height, unfortunately no information is present about the flow profile).

Backlayering in test 1, 3A, 4 and 8 was observed at 20 m upstream of the fire. Backlayering lengths may have been longer in the tests but beyond 20 m no temperatures were measured. The CFD calculations do show backlayering lengths up to 19 m (test 1), up to 17 m (test 3A), up to 15 m (test 4) and up to 35 m (test 8).

Several causes, both experimental and modelling, can be pointed out to explain the remaining differences between the measurement and the calculation data.

Since the RHR was not measured (this is infeasible) there is an uncertainty in the realised RHR's. For the fires with liquids used as a fuel the RHR is based on the tabulated effective heats of combustion [4] accounting proportionally for the composition of the fuel (two components). However, the overall combustion efficiency of these fires could have been dominated by the strongly smoke forming toluene and therefore be lower then estimated. The remaining uncertainty in the RHR is estimated to be 10-25% of the total RHR. The inaccuracy in the determination of the realised RHR may have caused the deviations in the calculated thickness of the smoke layer and the calculated temperatures. The same holds for the pallet fire where the RHR was based on the tabulated heat of combustion of wood not accounting for e.g. moisture variations.

Concerning the modelling it should be noted that buoyancy effects are not incorporated accurately when using the k-ε model with standard coefficients and the standard correction for buoyancy [2]. Other modelling aspects that could be significant are the absence of a combustion model and the use of a simplified radiation model having a limited accuracy in the calculation of heat losses in the fire area.

However due to the uncertainties in the experiment (realised RHR, velocities) assigning the remaining differences between measurements and calculations to specific modelling or experimental errors is difficult.

Transient results

The development of the RHR in test 8 shows a strong variation (figure 3). In test 4 the RHR was kept constant and the ventilation speed was varied between 1 and 6 m/s (figure 4). These aspects make test 4 and 8 suitable for the presentation of the transient calculation results showing the effect of varying RHR and ventilation flow. The measured and calculated temperatures are shown in figure 7 and 8 as a function of time for several distances from the fire. As is shown in these figures the calculated temperatures are consistent with the measured temperatures when the RHR or ventilation speed varied in the tests. As mentioned before the thickness of the smoke layer is over-predicted in the calculations which is also visible in these figures.

6. CONCLUSIONS

In this study a comparison was made between full-scale fire tests in a tunnel and (transient) CFD calculations of these tests. Comparison of the temperature profiles in the tunnel for fire tests under different conditions shows a clear and consistent dependence of these temperatures to the RHR of the fire and the ventilation speed in the tunnel during the fully developed phase of the fires. A transient analysis of the measured and calculated temperatures shows a consistent dependence of these temperatures with the RHR and the ventilation speed for the tests in which the RHR and ventilation flow were varied. The occurrence of backlayering was predicted, however the backlayering lengths were underestimated slightly.

The calculations show a reasonable agreement with the measured data. The observed differences can not be explained without more accurate insight in the conditions in the tunnel during the fires (RHR, flows).

The foregoing analysis leads to two main conclusions:

- The estimated accuracy of the calculations must be considered with respect to the uncertainty in the conditions in the tunnel during the fire tests due to experimental and measurement errors. To get a better insight in the predictive possibilities of CFD calculations (better than shown) it is necessary to perform tests with a great emphases on the detailed measurement of the conditions in the tunnel (temperature, air velocities, smoke density). Deviations in the realised RHR and the measurement errors do have a strong influence on the outcome of the measurements and therefore on the conclusions drawn concerning the predictive possibilities of CFD. These aspects do also restrict the number of tests suitable for validation purposes.
- The qualitative accuracy of the calculations performed is good. Overall phenomena like the occurrence of backlayering and stratification are predicted. The thickness of the smoke layer is over-predicted and the backlayering lengths are under-predicted for

which different causes can be pointed out. With the use of basic models in the description of turbulence and radiation the quantitative accuracy of the calculations performed is reasonable.

- The observed differences between measured and calculated temperatures is acceptable with respect to the uncertainty in the development of real fires in tunnels. It is shown that CFD calculations can be used as a predictive tool in the design of tunnels and tunnel installations. The use of this tool is economic and does not come with the risks involved with an in situ full-scale fire test.

REFERENCES

[1] 'Project 'Safety Proef', Rapportage brandproeven', Bouwdienst Rijkswaterstaat, Utrecht (2002)

[2] G. Cox et al, 'Combustion Fundamentals of Fire', Academic Press Limited, London (1995).

[3] http://cham.co.uk

[4] SFPE Handbook of Fire Protection Engineering, Third edition (2002)

[5] K.C. Karki, S.V. Patankar, E. Rosenbluth, S. Levy, 'CFD model for jet fan ventilation systems', Proceedings of the 10th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels (2000)

[6] S.Kumar, G.Cox, 'Radiant heat and surface effects in the numerical modelling of tunnel fires', Proceedings of the 10th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels (1988)

[7] Massachusetts Highway Department and Bechtel/Parsons Brinckerhoff, 'Memorial Tunnel Fire Ventilation Program', Test Report (1995)

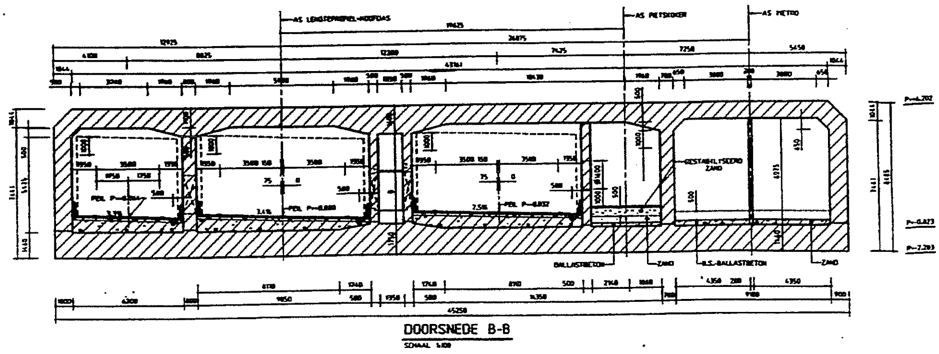

Figure 1: Cross section of tunnel

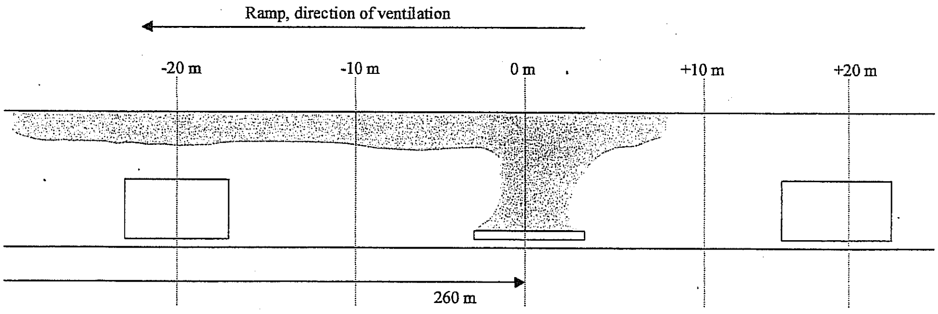

Figure 2: Schematic presentation of the fire site

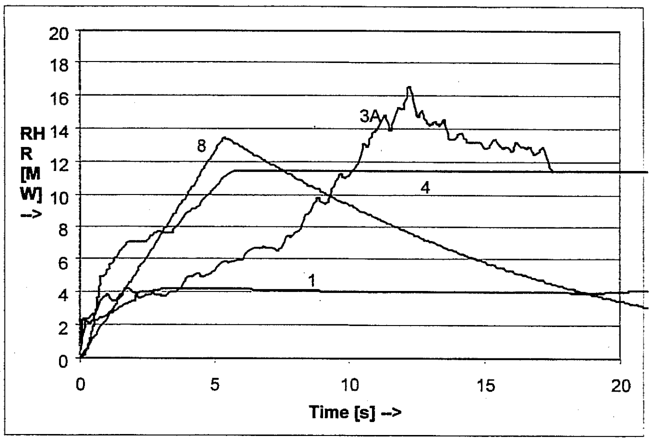

Figure 3: RHR as a function of time for the relevant tests (1, 3A, 4, 8)

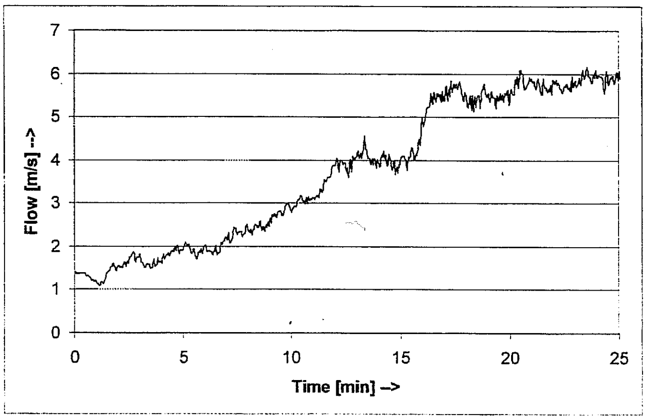

Figure 4: Ventilation speed as a function of time for test 4

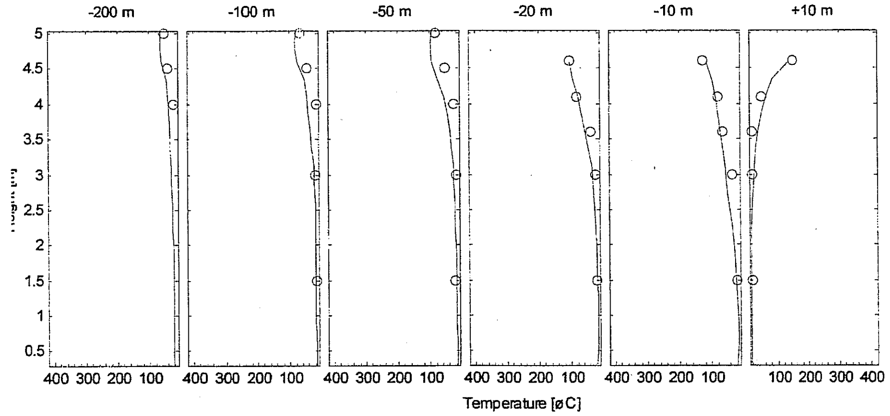

Figure 5a: Temperature profile in fully-developed phase of fire, calculations and measurements (test 1).

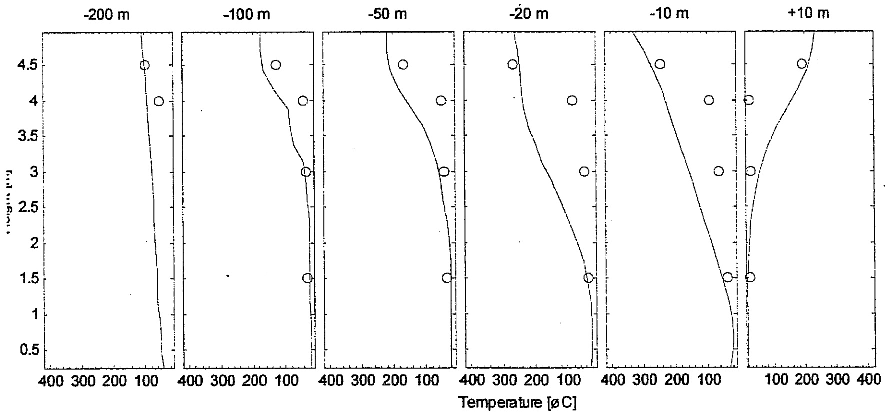

Figure 5b: Temperature profile in fully-developed phase of fire, calculations and measurements (test 3A).

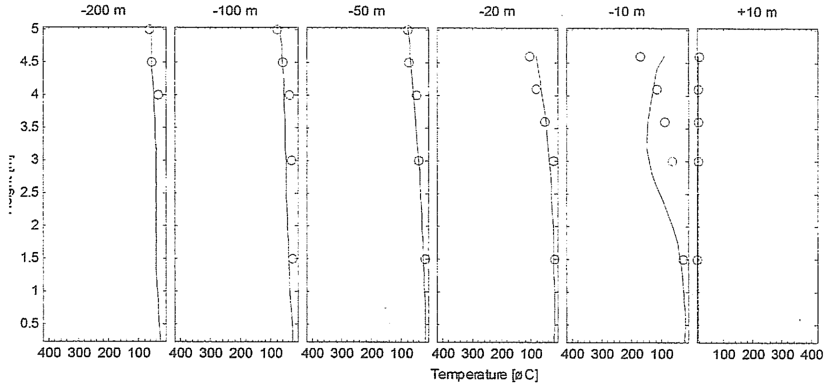

Figure 5c: Temperature profile in fully-developed phase of fire, calculations and measurements (test 4).

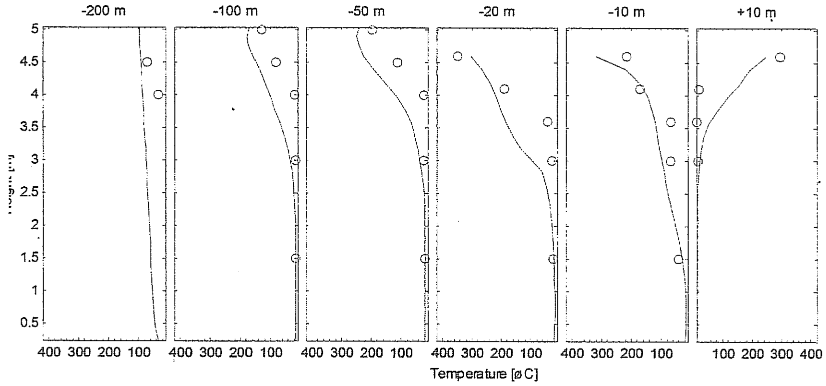

Figure 5d: Temperature profile in fully-developed phase of fire, calculations and measurements (test 8).

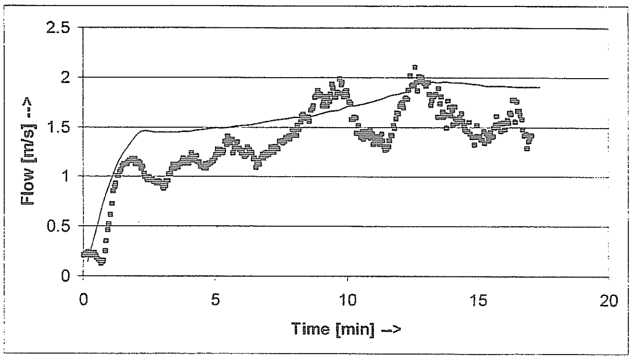

Figure 6 Measured and calculated flow test 3A

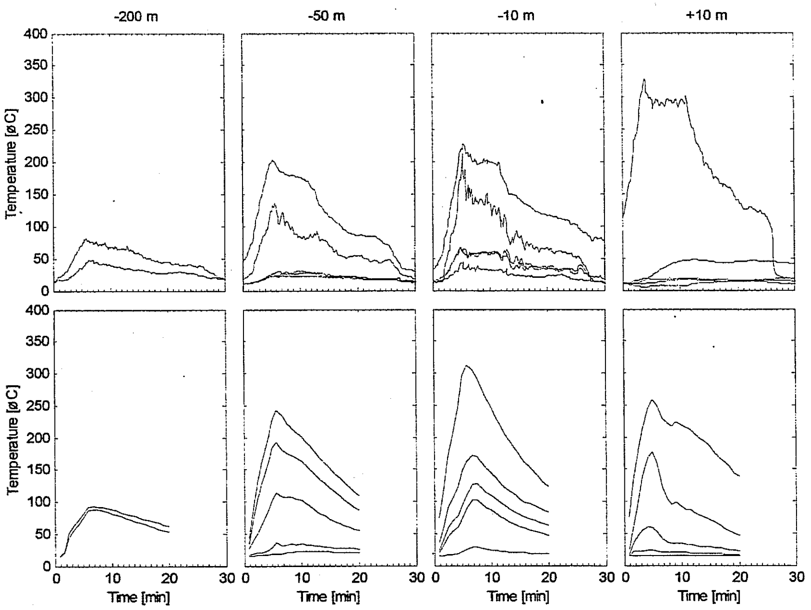

Figure 7: Variation of measured (top) and calculated (bottom) temperatures with RHR (test 8)

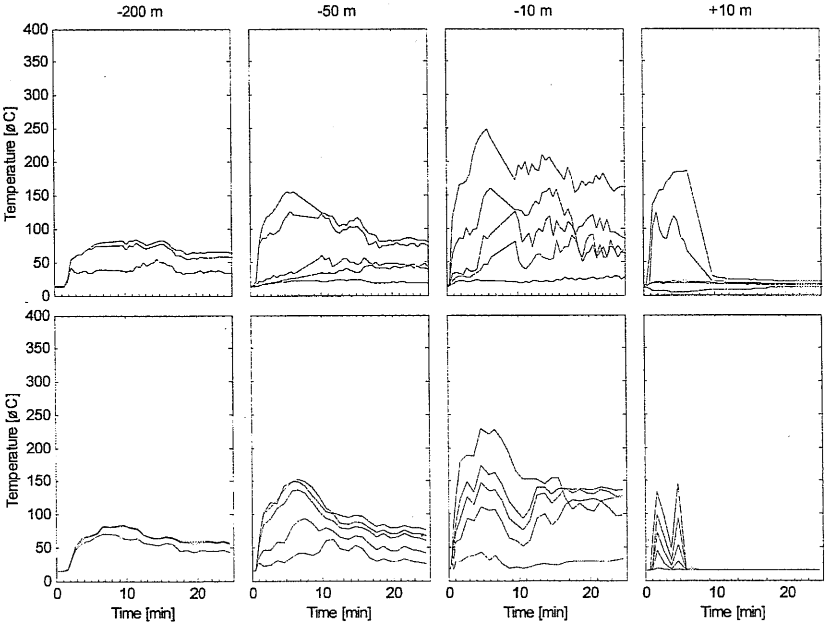

Figure 8: Variation of measured (top) and calculated (bottom) temperatures with ventilation flow (test 4)

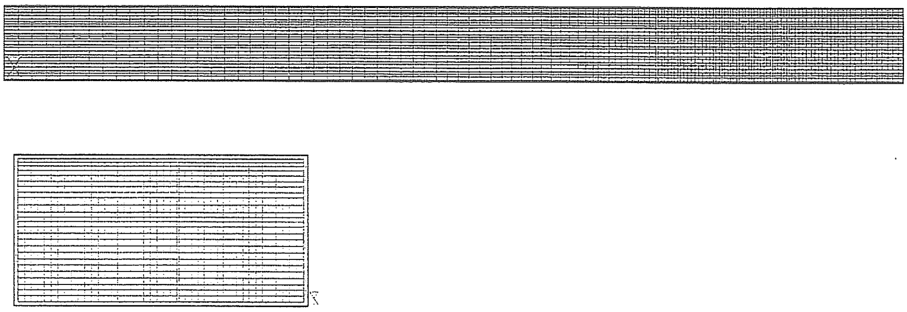

Figure 9: Mesh