Validation of Phoenics 3.5 for Modelling Tunnel Ventilation Systems Under Fire Conditions

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ABSTRACT

There is an increasing demand for performance-based design of tunnel emergency ventilation systems due to the various benefits that are attained from such an approach. In designing such systems, the performance of the ventilation system in the event of a fire is required to be assessed to determine whether the system is effective in maintaining a tenable environment for occupants to escape. Computational Fluid Dynamics (CFD) codes are used to assess the performance of these systems under fire conditions. The accuracy of such codes in predicting the conditions within the tunnel are critical to the success of the design. The accuracy of a CFD code may be assessed by validation using results from actual fire tests. This validation shows the potential differences that may occur between the numerical prediction and real fire events. However, in order to carry out this validation process, reliable and well documented reference data is needed.

The Memorial Tunnel Fire Ventilation Test Program consisted of a series of full-scale fire tests conducted in an abandoned road tunnel near Charleston, West Virginia. Various tunnel ventilation systems and configurations of such systems were operated under a number of design fires to assess their performance in managing the smoke and temperatures produced by the fire within the tunnel. The tunnel was equipped with instrumentation and recording equipment for obtaining data on air velocity, temperature, carbon monoxide and carbon dioxide at various tunnel sections.

These results provide a useful source for the validation of CFD codes, such as Phoenics 3.5, in modelling the effectiveness of tunnel ventilation systems under fire mode. A Phoenics 3.5 model was built to adequately represent the Memorial Tunnel utilising a natural ventilation system. The paper presents a comparison of the predicted results from the CFD models with the test results obtained in the fire tests.

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INTRODUCTION

Performance-based design of tunnel emergency ventilation systems can provide greater benefits than designing a system utilising a code or standard. A code compliant ventilation system design may, in some circumstances, result in the system being over designed for the project concerned or may not perform as expected. Therefore, designing the system on a performance basis may provide great cost and design benefits to the project, as the system may be designed in a proficient manner. However, in order to design such systems, sophisticated tools are required to assess the performance of the ventilation system under fire conditions.

The Computational Fluid Dynamics (CFD) package *Phoenics 3.5* may be utilised to model the likely flows and conditions that would occur within a space under fire conditions. However, in order to accurately model such conditions a number of assumptions are required to be made.

A previous study [1] has been conducted which validated the use of Phoenics 3.2 for modelling fires in tunnels incorporating a ventilation system with forced flow. This study assessed a longitudinal ventilation system only. Therefore, the objective of this study is to assess a natural ventilation system, utilising the parameters verified in the previous study, to further validate the use of *Phoenics* as a tool for modelling the effectiveness of tunnel ventilation systems under fire conditions.

THE MEMORIAL TUNNEL FIRE VENTILATION TEST PROGRAM

General

The Memorial Tunnel Fire Ventilation Test Program (MTFVTP) consisted of a series of full-scale fire tests conducted in an abandoned road tunnel near Charleston, West Virginia. Various tunnel ventilation systems and configurations of such systems were operated under a number of design fires to assess their performance in managing the smoke and temperatures produced by the fire within the tunnel. The tunnel was equipped with instrumentation and recording equipment for obtaining data on air velocity, temperature, carbon monoxide and carbon dioxide at various tunnel sections.

Description of Memorial Tunnel

The tunnel has a length of approximately 854m. There is a 3.2 percent upgrade from the south tunnel portal to the north tunnel portal. A general cross-section of the tunnel is provided in Figure 1. The total cross-sectional area of the tunnel is approximately 60m^2.

Fan rooms (that were previously utilised for mechanical ventilation systems) are located at each tunnel portal, which reduce the height of each tunnel portal to approximately 4 m.

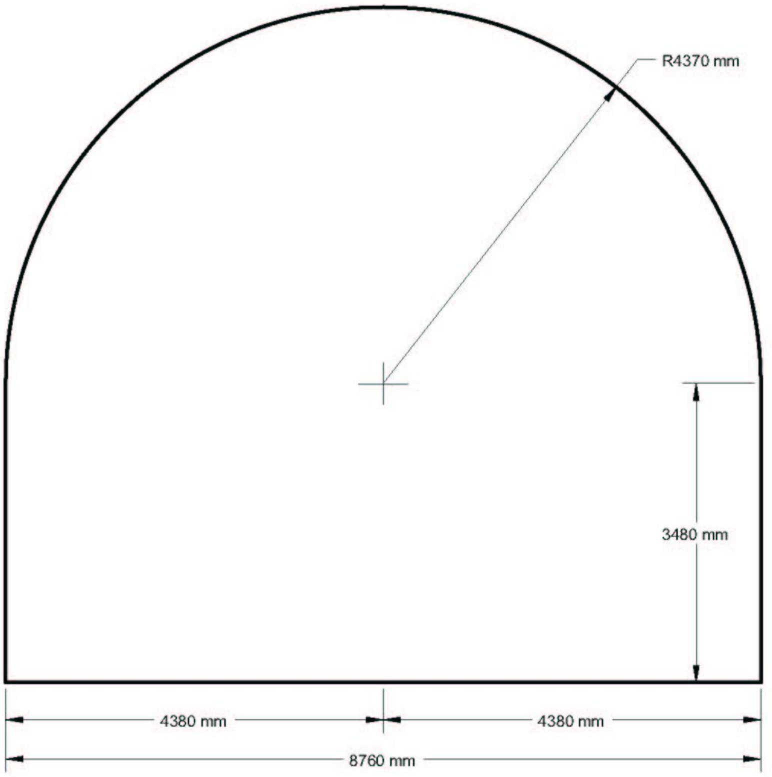

Figure 1 Memorial Tunnel Cross-Section

SCENARIO MODELLED

A natural ventilation system has been selected for analysis in this paper. Test 501 of the MTFVTP examined the effectiveness of natural ventilation in ventilating a 20MW fire.

The objective for this test was to measure the buoyancy driven airflows, air temperature and stratified smoke layers when no forced airflow is provided. The tunnel ceiling was removed for this test, resulting in the cross-section as shown in Figure 1. The fan rooms however were retained.

An ambient temperature of 7.22°C was observed in this test. The results obtained from the fire test for temperature and velocity contours at times of 1 minute, 5 minutes and 10 minutes are shown in Appendix A.

DESCRIPTION OF PHOENICS MODELS AND PARAMETERS USED

General

The CFD package *Phoenics 3.5* [2] developed by CHAM Ltd UK was used in this assessment. The special purpose version *Flair* was utilised to model the likely flows that would occur within the tunnel under fire conditions.

Phoenics Parameters

The geometry of the model was built using VR Editor, with the following parameters specified:

- A Cartesian coordinate system and mesh were used
- 40 time steps were used over the 10 minute simulation period (15 seconds per time step) [*]
- Gravitational acceleration was specified as follows to simulate the 3.2% grade in the tunnel;

  $x = 0$, $y = -9.8\ \text{m/s}^2$, $z = -0.31\ \text{m/s}^2$

- The validation report for Phoenics 3.2 referenced previously, verified various parameters required for modelling fires in tunnels. Some of these have been adopted for use in this assessment and are summarised as follows:
  - *k-e* turbulence model; and
  - buoyancy effect on turbulence was included with a coefficient of 0.1.

Description of Models

The parameters described above were employed in all of the models. The distinctive characteristics of each of the models are summarised in Table 1.

Run	Grid (X x Y x Z)	Iterations per time step	Solids, walls properties	Roughness	Heat Release Rate
1	40 x 37 x 461	40	7.22 °C fixed temperature	0.01m	Based upon elapsed time
2	68 x 62 x 606	40	7.22 °C fixed temperature	0.01m	Based upon elapsed time
3	31 x 23 x 348	40	7.22 °C fixed temperature	0.01m	Based upon elapsed time
4	40 x 37 x 461	25	7.22 °C fixed temperature	0.01m	Based upon elapsed time
5	40 x 37 x 461	50	7.22 °C fixed temperature	0.01m	Based upon elapsed time
6	40 x 37 x 461	50	7.22 °C fixed temperature	0.01m	Adjusted to take into account burning before elapsed time
7	40 x 37 x 461	50	7.22 °C fixed temperature	0.001m	Adjusted to take into account burning before elapsed time
8	40 x 37 x 461	50	Adiabatic	0.001m	Adjusted to take into account burning before elapsed time

Table 1 CFD Run Parameters

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[*] Chosen based upon prior experience

Fire Modelling

The fire is represented by a number of blocks which "turn on" and "turn off" throughout the run to simulate the growth of the fire. The material of each block is specified as domain material. To ensure that realistic fire temperatures are achieved, each block is set with a heat release rate per unit volume of 1MW/m^3. Radiation has not been modelled in these Phoenics runs and therefore the radiative component of the heat release rate has been deducted from the total heat release rate when defining the fire in Phoenics. A percentage of 30% has been taken for the radiative component of the heat release rate, which is a well established value [3].

The representation of the heat release rate of the fire modelled in Phoenics is illustrated in Figure 2. This is based upon the actual heat release rate given in the MTFVTP Test 501 data. The fire is located approximately 238m north of the southern portal.

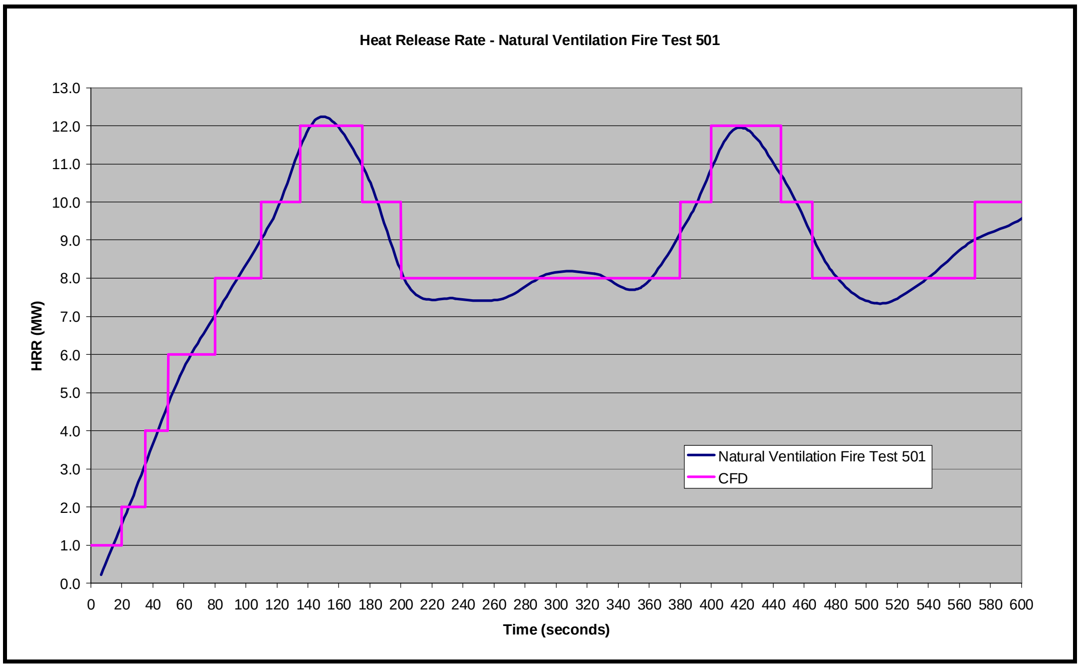

Figure 2 Heat release rate (radiative component deducted)

RESULTS

Comparison of Results – Runs 1 to 5

Table 2 below shows a summary of the comparison of Phoenics runs 1 to 5 with the results obtained in the MTFVTP fire tests. The output from the MTFVTP Test 501 is shown in Appendix A, with the output from Phoenics runs 1 to 5 shown in Appendix B through to Appendix F.

Run	Temperature			Velocity		
	1 minute	5 minutes	10 minutes	1 minute	5 minutes	10 minutes
1 Intermediate grid 40 iterations per time step 0.01m roughness	Generally, near the fire the temperature is over-predicted. Temperatures immediately uphill and downhill of the fire are grossly over-predicted. However, the hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Same comments as for 1 minute.	Temperatures throughout the tunnel are generally over-predicted, with the difference in temperature increasing as the distance to the fire decreases. The over-prediction in temperature varied from approximately 100°F away from the fire, to approximately 300°F near the fire.	Velocities at the ceiling immediately uphill of the fire are over-predicted by approximately 400 fpm. Velocities at the ceiling immediately downhill of the fire and velocities around the fire at low level are relatively close to those observed in the fire tests. However, away from the fire, velocities were generally under predicted.	Velocities uphill at the ceiling are over-predicted, but everywhere else are generally under-predicted.	Velocities are generally over-predicted throughout the tunnel by up to approximately 800fpm at high level uphill of the fire, and generally 600fpm for the remainder of the space.
2 Fine grid 40 iterations per time step 0.01m roughness	Temperatures immediately uphill of the fire are over-predicted by approximately 100°F. The hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Approximately the first 200m uphill of the fire is generally in agreement with the test results. However, the 100°F contour did not spread as far up the tunnel as it did in the fire test. Downhill of the fire, temperatures are generally over-predicted by approximately 100°F.	Temperatures are over-predicted by 100°F immediately downhill of the fire, and by approximately 200°F further downhill. Uphill of the fire, the first 200m is in agreement with the test results, but the remainder of the uphill section is under-predicted. Generally, the hot smoke layer has not	Velocities uphill of the fire at the ceiling are over-predicted. Velocities away from the fire are under-predicted.	Velocities are over-predicted for the first 200m uphill of the fire, then they are under-predicted until just near the uphill portal, where they become slightly over-predicted again. Downhill of the fire velocities are generally in agreement with the test results, except they are under-predicted at the	Velocities are over-predicted uphill of the fire until approximately 200-300m uphill of the fire where they become under-predicted. Velocities are very under-predicted downhill of the fire.

Run	Temperature			Velocity		
	1 minute	5 minutes	10 minutes	1 minute	5 minutes	10 minutes
			spread as far up the hill as it did in the fire test.		downhill portal.	
3 Coarse grid 40 iterations per time step 0.01m roughness	Temperatures immediately uphill of the fire are approximately 100°F above those obtained in the fire test. The hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Uphill of the fire temperatures are in agreement with the test results for the first 200m. Further uphill the 100°F contour has not spread as far. Temperatures are generally over-predicted by approximately 100°F downhill of the fire.	Temperatures are in fairly good agreement except that they are over-predicted at the ceiling. The difference in temperature increases as you move closer to the fire. Results are over-predicted by approximately 200°F near the fire and 100°F away from the fire.	Velocities are over-predicted at the ceiling near the fire, but are under-predicted at low level. Velocities are under-predicted at the downhill portal but reasonable at the uphill portal.	Velocities are over-predicted for the first 200m uphill of the fire, but are under-predicted further uphill. Velocities are in agreement with the test results at the uphill portal. Velocities are slightly under-predicted downhill of the fire.	Velocities are generally over-predicted throughout the tunnel by on average 400fpm, except at around 200m uphill of fire where they are in agreement with the test data.
4 Intermediate grid 25 iterations per time step 0.01m roughness	Temperatures are grossly over-predicted near the fire at the ceiling (uphill 200°F to 300°F, downhill approximately 100°F). The hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Temperatures near the fire are over-predicted by approximately 150°F to 300°F. However, the hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Temperatures are over-predicted 100m either side of the fire by approximately 200°F to 400°F. The 100°F contour spread a fair way up the tunnel (close to it did in the fire test) but hasn't dropped as low as it did in the fire test.	Velocities are slightly over-predicted immediately uphill of the fire at the ceiling. Velocities are under-predicted at low level for the first 100m uphill of the fire. They are generally in agreement with the test results throughout the remainder of the space.	Velocities are over-predicted for the first 200m uphill of the fire, but are under-predicted further uphill of that. Velocities are under-predicted at low level near the portals. Downhill of the fire velocities are under-predicted at low level but in agreement with the test results at high level.	Velocities are over-predicted for the first 200m uphill of the fire, but are under-predicted further uphill of that, except at the portal where they are in agreement with the test results. Velocities are slightly under-predicted downhill of the fire, except at high level at the downhill portal where they are over-predicted.

Run	Temperature			Velocity		
	1 minute	5 minutes	10 minutes	1 minute	5 minutes	10 minutes
5 Intermediate grid 50 iterations per time step 0.01m roughness	Temperatures near the fire at the ceiling are over-predicted by approximately 100^{o}F to 200^{o}F. The hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Temperatures are over-predicted downhill of the fire and for the first 300m uphill of the fire. However, the hot smoke layer predicted by Phoenics did not spread as far up the tunnel as it did in the fire test.	Temperatures are in agreement with the test results uphill of the fire except the hot layer is lower than in the fire test. There is also a “hot patch” near the uphill fan room. Temperatures are over-predicted downhill of the fire, but the hot layer has not spread as far downhill.	Velocities are over-predicted at the ceiling uphill of the fire, but are under-predicted at low level. Further uphill of the fire they are slightly under-predicted. Velocities are under-predicted downhill of the fire.	Velocities are over-predicted near the fire but they approach the test results as the distance from the fire increases. Velocities are slightly under-predicted downhill of the fire. At the downhill portal, the velocity distribution is different to that observed in the test.	Airflow patterns were in agreement with the fire test, but velocities are generally over-predicted by approximately 400fpm (800fpm near the fire at the ceiling). 200m uphill of the fire the velocities are in good agreement with the test results. Velocities are over-predicted at the portals.

Table 2 Comparison of Runs 1 to 5 with MTFVTP Test 501

Discussion on Runs 1 to 5

Phoenics Results

Generally temperatures and velocities were over-predicted near the fire for all three times shown. However, at a time of 1 minute and 5 minutes, temperatures and velocities were under-predicted away from the fire. This lead to the hot smoke layer predicted by Phoenics not spreading as far up the tunnel as it did in the fire test. At 10 minutes, temperatures and velocities were generally over-predicted throughout the space.

An exception to this is run 2, where there was generally more under-prediction throughout. This run involved a finer grid with 40 iterations per time step. It is considered that due to the smaller cell sizes, that 40 iterations was not sufficient in obtaining a converged solution and perhaps more iterations were required.

Run 5 gave results that were the closest to the results obtained in the fire test. This run involved an increased number of iterations per time step (50), with the intermediate grid. These results gave airflows and temperatures at 10 minutes that were generally in good agreement, except for some over-prediction. However, for times of 1 minute and 5 minutes, the smoke layer still did not spread as far up the tunnel as it did in the fire test.

Therefore, some further investigation was required in order to determine the reason for this under-prediction at the earlier times.

MTFVTP "Elapsed Time"

The data and output from MTFVTP Test 501 that was used in setting up the Phoenics model and comparing results are listed below:

1. Heat release rate of the fire;
2. Temperature contours through the centre of the tunnel; and
3. Velocity contours through the centre of the tunnel.

The times given in this MTFVTP data and output were based upon an elapsed time. In order to appreciate the effect of this elapsed time, the test events sequence for Test 501 is shown below.

Test Events Sequence

	Real Time (hr:min:sec)	Elapsed Time (min:sec)
Ignitor Ignition:	11:28:25	
Fuel Oil Ignition:	11:28:50	
Full Pan Engulfment:	11:29:46	0:00
Fuel Oil Shut-Off	11:54:46	25:00
Pan Fuel Oil Burnout:	No visual observation of this event.	

Test was concluded at 11:57:45 when the Central Fans were initiated.

It can be seen that the elapsed time started when full pan engulfment occurred, which is approximately 1 minute after ignition of the fuel oil. The heat release rate given for Test 501 started at this elapsed time with a heat release rate of 0. However, it is considered that the heat release rate of the fire at full pan engulfment would be close to the peak heat release rate achieved. Therefore, there is potentially 1 minute prior to the start of the Phoenics runs where there is a rapidly growing fire present within the tunnel. Further to this, not only is the model missing 1 minute of fire growth, it also has a significant delay in the time it takes for the fire to reach its peak heat release rate.

Calculation of Heat Release Rate

During the test, fuel was pumped into the fuel pan to maintain a constant amount of fuel within the pan. The amount of fuel pumped into the pan was determined by the weight of the pan. The pan had weight cells beneath it which gave feedback to a controller on the weight of the pan. Once the weight decreased, fuel was pumped into the pan. The heat release rate was calculated on the mass consumption, which was determined by the amount of fuel pumped into the pan.

It is important to note that a fire plume produces turbulent flows which may have an affect on the weight measurements obtained, due to the forces it produces on the pan (particularly in large fires such as this). Looking at the pan weights and corresponding heat release rate data, this turbulent nature can be seen by the fluctuations observed in the weight measurements. Therefore, it is considered that weighing the pan may not be the most accurate method of measuring the amount of fuel in the pan and consequently the amount of fuel consumption. (Perhaps a more appropriate method would be to monitor the height of the fuel levels within the pan by a sensor.)

Adjustments to Phoenics Model

It was considered appropriate to adjust the heat release rate to take the factors discussed above into account. The heat release rate was adjusted in two ways. Firstly, the Phoenics model was run for an extra 1 minute to allow for the burning that occurred prior to the elapsed time. During this 1 minute, the fire was grown to its maximum heat release rate, as it is considered that at full pan engulfment this would be the case. Secondly, the maximum heat release rate was averaged out to compensate for the uncertainties in the measured heat release rate. The adjusted heat release rate is shown in Figure 3 below.

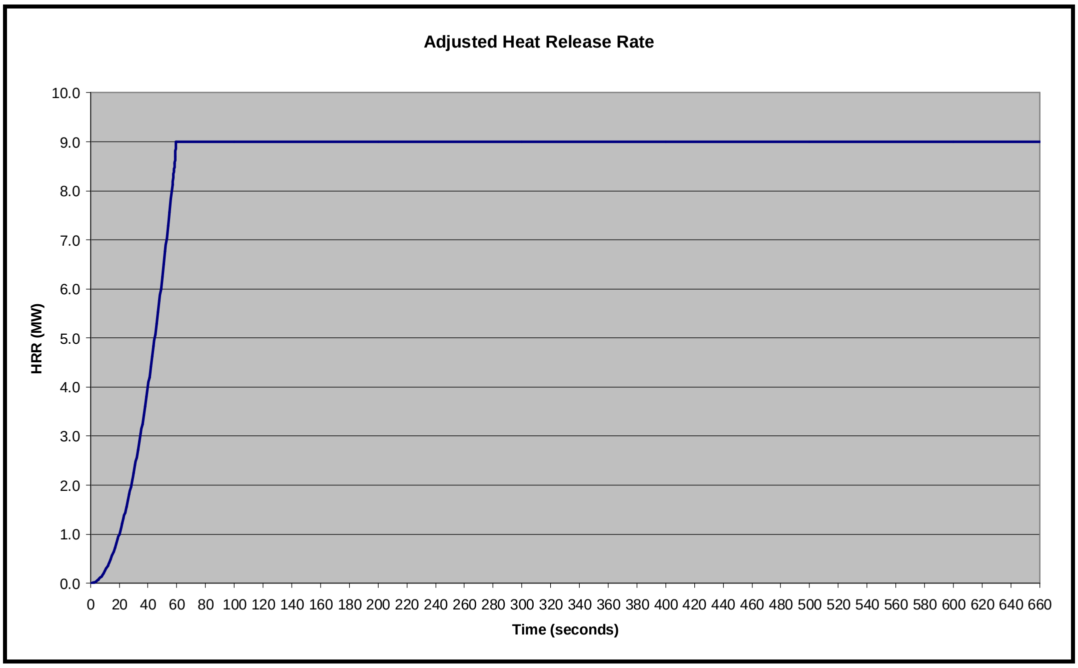

Figure 3 Adjusted Heat Release Rate (radiative component deducted)

Comparison of Results – Runs 6 to 8

Table 3 below shows a summary of the comparison of Phoenics runs 6 to 8 with the results obtained in the MTFVTP fire tests. The output from the MTFVTP Test 501 is shown in Appendix A, with the output from Phoenics runs 6 to 8 shown in Appendix G through to Appendix I.

Run	Temperature			Velocity		
	1 minute	5 minutes	10 minutes	1 minute	5 minutes	10 minutes
6 Adjusted HRR Intermediate grid 50 iterations per time step 0.01m roughness	Temperatures near the fire are over-predicted by 400ºF near the fire and 100ºF further away. The spread of the layer uphill is slightly under-predicted. The spread downhill is also under-predicted.	Temperatures above the fire are similar to those obtained in the test. 50m to 100m away from the fire they become over-predicted. The layer has not spread as far both uphill and downhill.	Temperatures are in good agreement with the results obtained in the fire test. The hot layer has dropped a little lower uphill, and did not spread quite as far down the tunnel downhill.	Velocities are over-predicted at the ceiling uphill of the fire, but are slightly under-predicted at the downhill portal. Elsewhere they are generally in fair agreement with the fire test results.	Velocities are generally over-predicted. Immediately downhill of the fire and at the portals they are in fair agreement with the test results.	The flow patters resemble those observed in the fire test. However, velocities are generally over-predicted throughout.
7 Adjusted HRR Intermediate grid 50 iterations per time step 0.001m roughness	Temperatures near the fire are over-predicted by 400ºF near the fire and 200ºF further away. The spread of the layer uphill and downhill is under-predicted.	Temperatures are over-predicted throughout by up to 200ºF. Immediately above the fire temperatures are similar to those obtained in the test. Although the hot layer has spread further uphill than in any other Phoenics run, it still has not spread as far as it did in the fire test.	Temperatures immediately above the fire are similar to those obtained in the fire test. Uphill, the hot layer has dropped much lower (to the floor). The hot layer has not spread as far downhill.	Velocities are over-predicted at the ceiling uphill of the fire, but are under-predicted at low level uphill of the fire and at the downhill portal. Elsewhere they are generally in fair agreement with the test results.	Velocities are over-predicted throughout except at the portals.	Velocities are very over-predicted throughout the tunnel, except at the ceiling immediately downhill near the fire and for a region 300m-400m uphill of the fire. Flow patterns differ to those observed in the fire test.

Run	Temperature			Velocity		
	1 minute	5 minutes	10 minutes	1 minute	5 minutes	10 minutes
8 Adjusted HRR Intermediate grid 50 iterations per time step 0.001m roughness Adiabatic walls and solids	Temperatures are grossly over-predicted near the fire (by 300-500^{o}F). The hot layer has not spread as far uphill or downhill as it did in the fire test.	Temperatures are over-predicted for the first 200m uphill of the fire. They are also over-predicted near the fire downhill. The hot layer has spread a little further in this run, but still not as far as in the fire test.	Temperatures are very over-predicted uphill away from the fire. However, near the fire and downhill of the fire they are under-predicted.	Velocities are over-predicted by up to 600 fpm at the ceiling uphill near the fire. Velocities are under-predicted at the downhill portal.	Velocities are over-predicted for the first 200m uphill at both high and low level. The velocity profile at the downhill portal is different to that observed in the fore test.	Velocities are very over-predicted throughout the tunnel. There is some resemblance of flow patterns observed in the fire test, but the high velocities have seemed to have distorted this.

Table 3 Comparison of Runs 6 to 8 with MTFVTP Test 501

Discussion on Runs 6 to 8

The adjustment of the heat release rate has improved the results in the initial stages with the hot layer spreading further in run 6 than in runs 1 to 5. However, the spread is still not as extensive as that observed in the fire test. For run 6, the temperatures and velocities are in good agreement at a time of 10 minutes, with some small over-predictions.

Run 7 included a relatively small wall roughness to examine its effect on the flows within the tunnel to see whether the original judgment of this value was the cause for the hot layer not spreading as far up the tunnel. Although the hot layer did spread a little further than in the other Phoenics runs, it still did not spread as far in the earlier stages as it did in the fire test. At a time of 10 minutes, the hot layer dropped quite low uphill and the flow patterns throughout were different to those observed in the fire test and also in Phoenics run 6. There was generally more over-prediction observed throughout the tunnel than in Phoenics run 6. Therefore, it is considered that a wall roughness of 0.01m provided better results in modelling the tunnel.

Similarly, run 8 incorporated adiabatic conditions specified for walls and solids to assess whether this would have an impact on the spread of the hot layer. The results of this run did show an increase in spreading of the hot layer uphill for the earlier times, however this came with gross over-predictions of temperature and velocity. Furthermore, at a time of 10 minutes, temperatures were under-predicted near the fire and downhill of the fire (It should be noted that temperatures near the fire at a time of 10 minutes were not under-predicted in any other Phoenics run). Temperatures were over-predicted uphill of the fire by more than they were in the other Phoenics runs. Therefore, it was considered that a fixed temperature condition was a better assumption for the properties of walls and solids within the domain.

After comparing these results, it must also be borne in mind that a CFD model is a model only and is only a representation of what is likely to occur. Computational Fluid Dynamics is not an exact science and would never exactly predict what may occur at a particular time on a particular day. Fire itself has an erratic nature and the results from fire tests may even vary from test to test. Therefore, it is considered that the results of Phoenics run 6 show that Phoenics 3.5 may be used to predict the likely flows that would occur within a tunnel under fire conditions where natural ventilation is used, particularly once the buoyant driven airflows become well established.

CONCLUSIONS

Phoenics run 6 gave results which best represented the temperature and velocity profiles obtained in MTFVTP Test 501. This run incorporated the following parameters:

- A grid size of 40 x 37 x 461 cells;
- 50 iterations per time step;
- Solids and walls set to a 7.22 ^{o}C fixed temperature;
- A global wall roughness of 0.01m; and
- The heat release rate was adjusted to take into account the burning before the elapsed time.

The results obtained from this Phoenics run indicated that at a time of 10 minutes, the predicted conditions within the tunnel are in good agreement with the test data. However, for earlier times the spread of the hot layer was under-predicted. This under-prediction is not necessarily a failure in the ability of Phoenics to predict the likely flows within the space, but may be due to the uncertainty in the heat release rate measured in the fire test.

Based upon the observations made in the assessments, the following conclusions were drawn:

- Defining appropriate parameters and assumptions for modelling a fire in a tunnel utilising a natural ventilation system where the buoyancy driven airflows are the key driving force in the system is much more critical than in forced flow problems.
- The fire growth in the initial stages has a significant impact on the conditions within the tunnel during the early stages of the fire. However, upon reaching a time of 10 minutes, steady state conditions were approached.
- Adiabatic conditions specified for walls and solids resulted in gross over-predictions. Therefore, fixed temperature conditions are recommended for walls and solids within the domain.
- When using results obtained from a fire test:
    - It is important to look at the procedures of the test, including the source used to generate heat and smoke, how this source is measured and quantified, and when and how this source was ignited or initiated.
    - Also, the nomenclature used in the test results must be clearly understood. Terms such as the “elapsed time” in the MTFVTP require close attention in interpreting and using the test results.

Therefore, it is considered that the results of Phoenics run 6 show that Phoenics 3.5 may be used to predict the likely flows that would occur within a tunnel under fire conditions where natural ventilation is used, particularly once the buoyant driven airflows become well established. However, it is recommended that further research be done in validating Phoenics 3.5 for use in naturally ventilated scenarios using data from other fire tests.

REFERENCES

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5. Phoenics Documentation (Version 3.5), CHAM, 10 September 2002

APPENDIX A MTFVTP RESULTS – NATURAL VENTILATION [†]

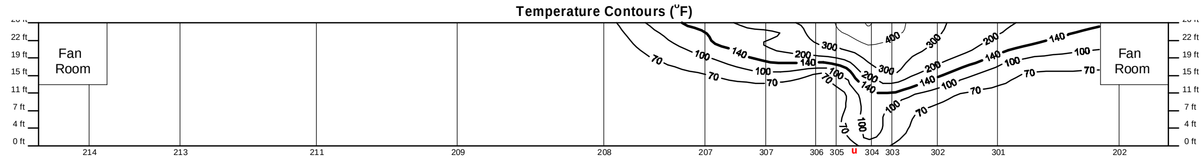

Figure 4 Temperature contours at a section through the centre of the tunnel at 1 minute

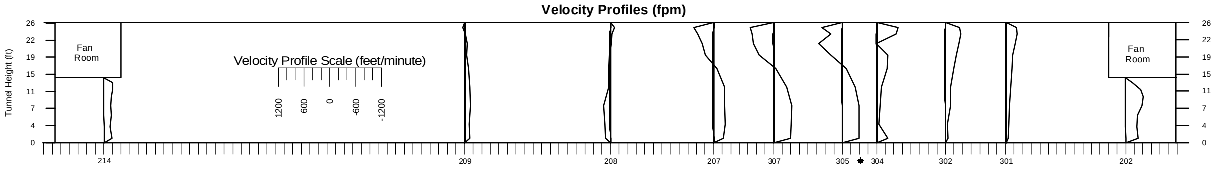

Figure 5 Velocity contours at a section through the centre of the tunnel at 1 minute

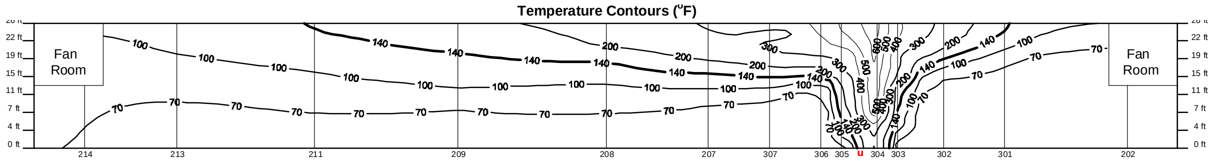

Figure 6 Temperature contours at a section through the centre of the tunnel at 5 minutes

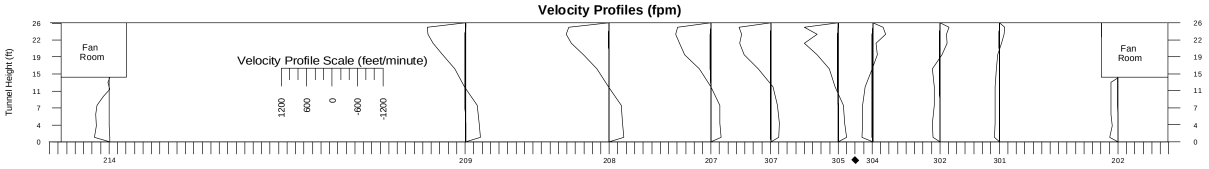

Figure 7 Velocity contours at a section through the centre of the tunnel at 5 minutes

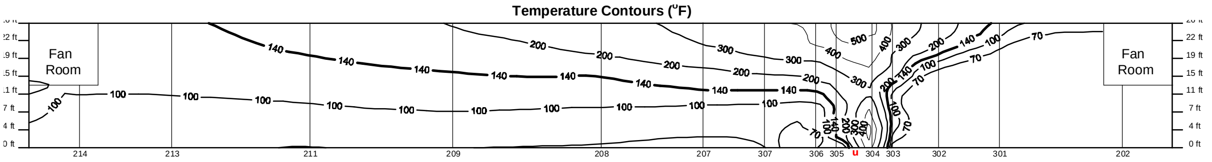

Figure 8 Temperature contours at a section through the centre of the tunnel at 10 minutes

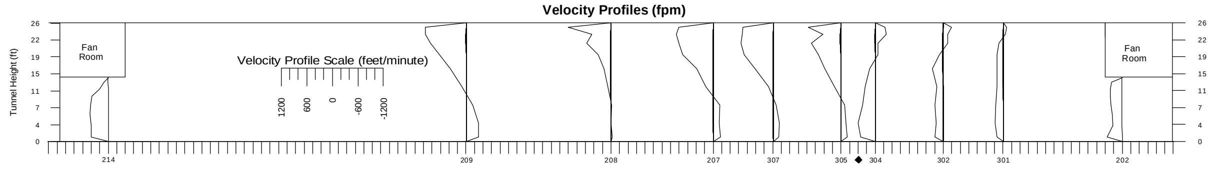

Figure 9 Velocity contours at a section through the centre of the tunnel at 10 minutes

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[†] Reproduced from Reference 4

Presentation of Results

The Photon module was used to obtain the output shown in this paper. Temperature and velocity contours at a section through the centre of the tunnel were plotted for times of 1 minute, 5 minutes and 10 minutes. The general layout of the Photon contour output is shown in Figure 10.

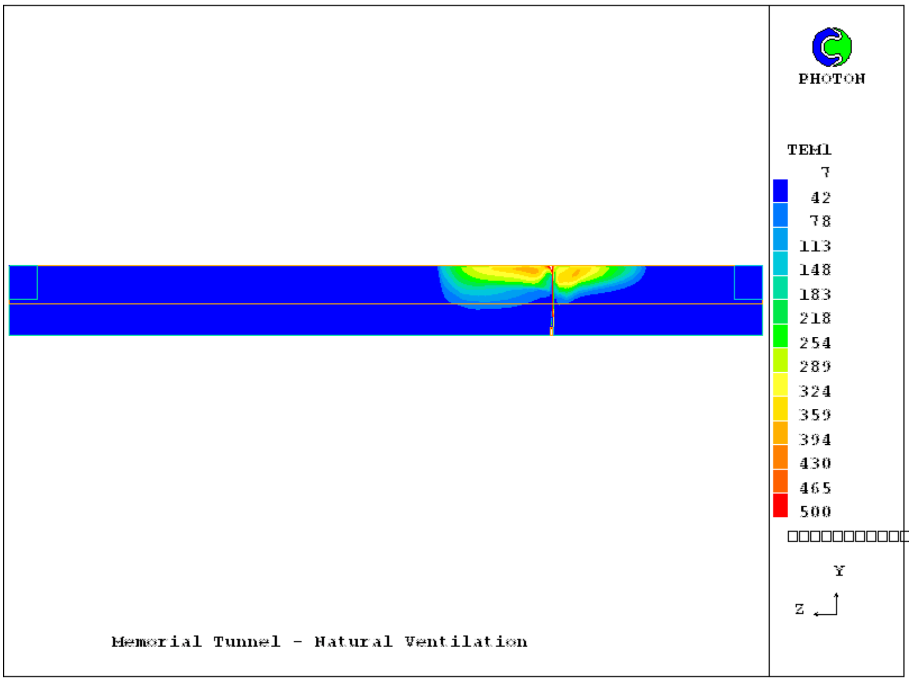

Figure 10 Photon Temperature Contour Output

The Phoenics output in Appendices B to I have been cropped to provide a better presentation of the results. The scales for the temperature and velocity contours are shown in Figure 11 and Figure 12 respectively. Phoenics uses metric units, with temperature given in degrees Celsius and velocity in metres per second. However, the MTFVTP results are given in imperial units, with temperature given in degrees Fahrenheit, and velocity given in feet per minute. Therefore, for ease of comparison between results, the units on the Phoenics scales shown in Figure 11 and Figure 12 below have been converted to the respective imperial units.

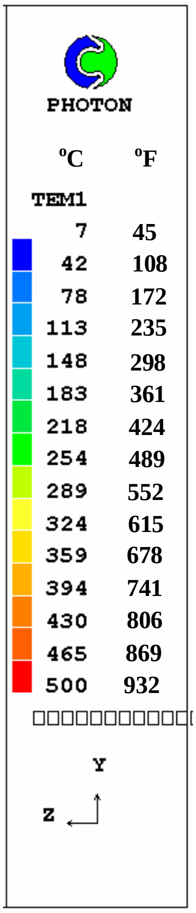

Figure 11 Temperature Scale for Photon Output

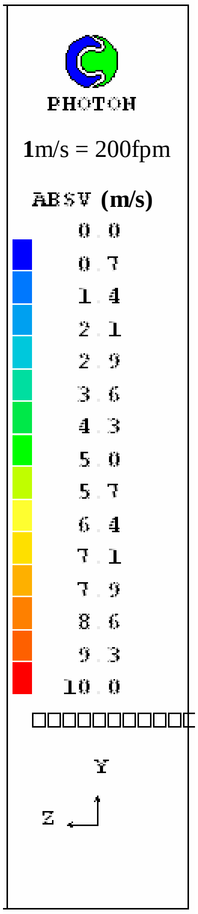

Figure 12 Velocity Scale for Photon Output

APPENDIX B CFD RESULTS – NATURAL VENTILATION – RUN 1

Figure 13 Temperature contours at a section through the centre of the tunnel at 1 minute

Figure 14 Velocity contours at a section through the centre of the tunnel at 1 minute

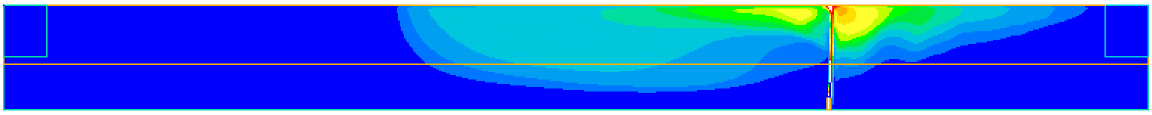

Figure 15 Temperature contours at a section through the centre of the tunnel at 5 minutes

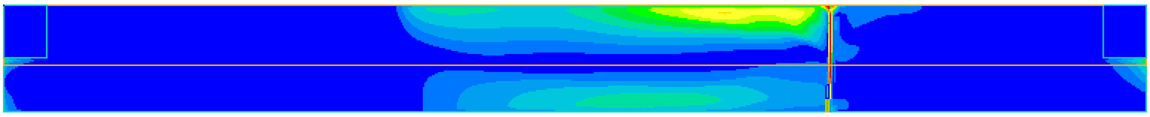

Figure 16 Velocity contours at a section through the centre of the tunnel at 5 minutes

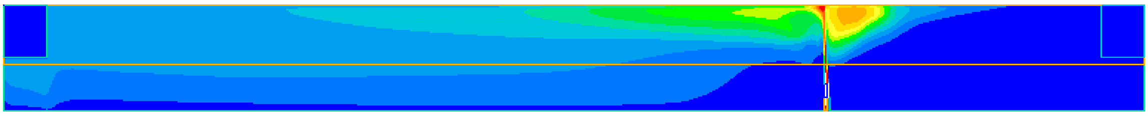

Figure 17 Temperature contours at a section through the centre of the tunnel at 10 minutes

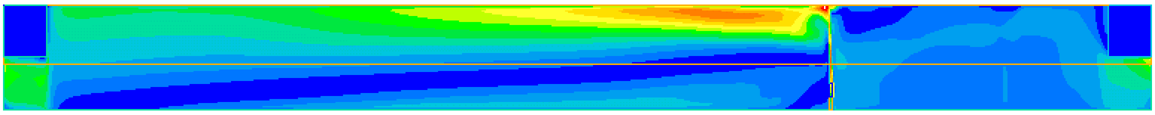

Figure 18 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX C CFD RESULTS – NATURAL VENTILATION – RUN 2

Figure 19 Temperature contours at a section through the centre of the tunnel at 1 minute

Figure 20 Velocity contours at a section through the centre of the tunnel at 1 minute

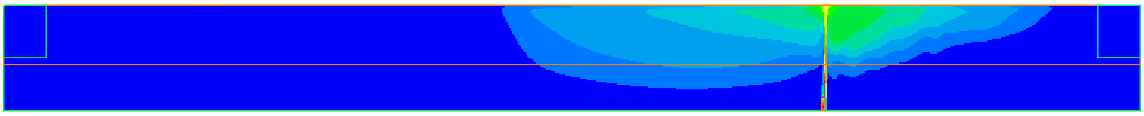

Figure 21 Temperature contours at a section through the centre of the tunnel at 5 minutes

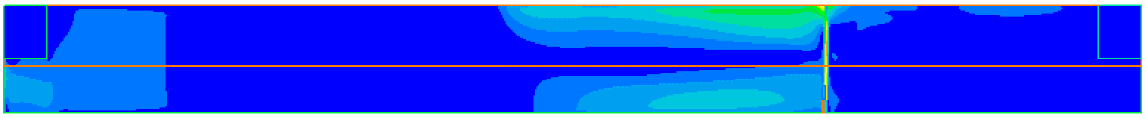

Figure 22 Velocity contours at a section through the centre of the tunnel at 5 minutes

Figure 23 Temperature contours at a section through the centre of the tunnel at 10 minutes

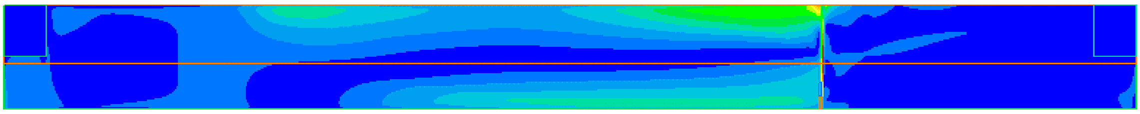

Figure 24 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX D CFD RESULTS – NATURAL VENTILATION – RUN 3

Figure 25 Temperature contours at a section through the centre of the tunnel at 1 minute

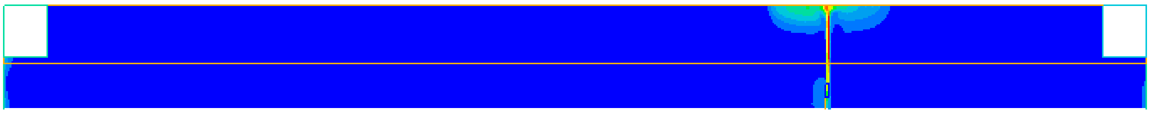

Figure 26 Velocity contours at a section through the centre of the tunnel at 1 minute

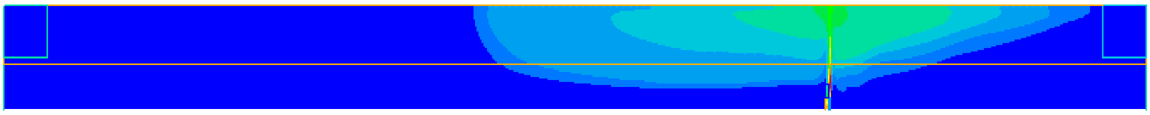

Figure 27 Temperature contours at a section through the centre of the tunnel at 5 minutes

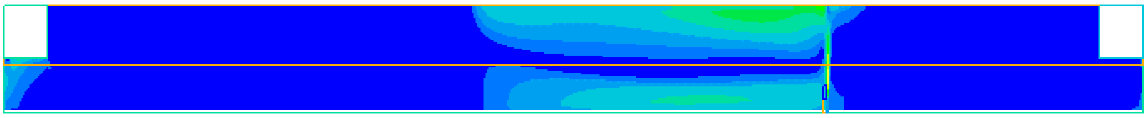

Figure 28 Velocity contours at a section through the centre of the tunnel at 5 minutes

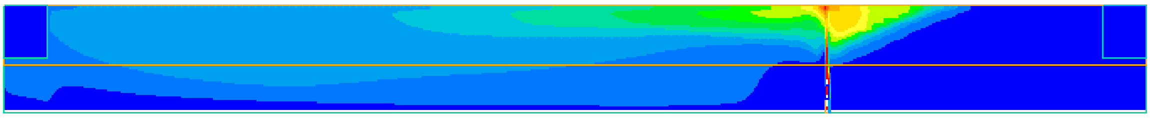

Figure 29 Temperature contours at a section through the centre of the tunnel at 10 minutes

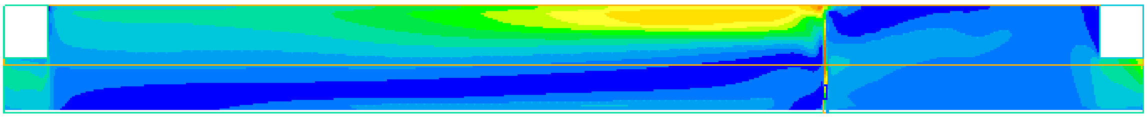

Figure 30 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX E CFD RESULTS – NATURAL VENTILATION – RUN 4

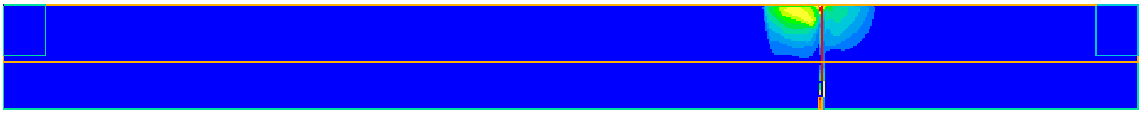

Figure 31 Temperature contours at a section through the centre of the tunnel at 1 minute

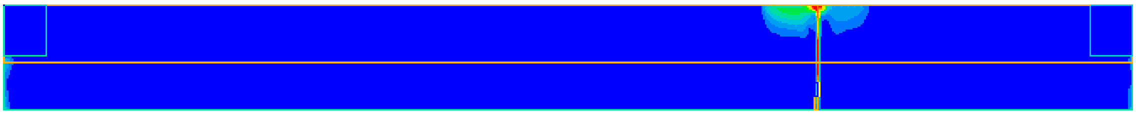

Figure 32 Velocity contours at a section through the centre of the tunnel at 1 minute

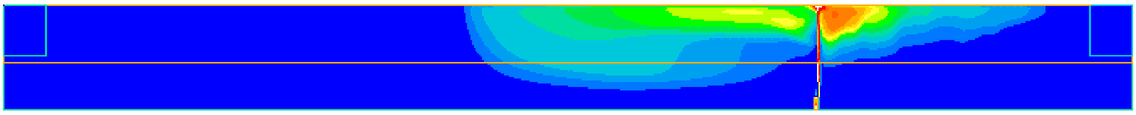

Figure 33 Temperature contours at a section through the centre of the tunnel at 5 minutes

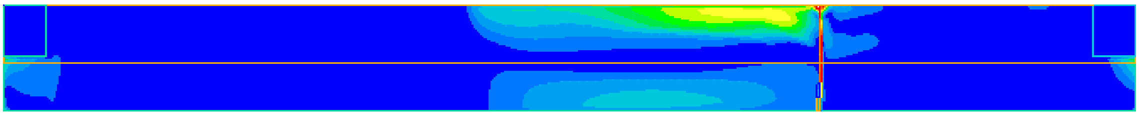

Figure 34 Velocity contours at a section through the centre of the tunnel at 5 minutes

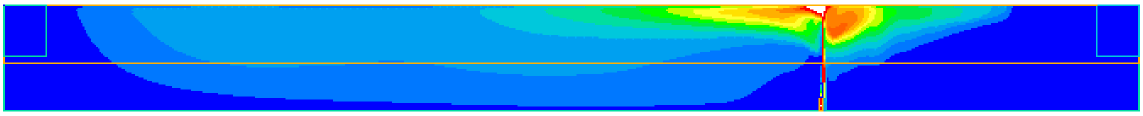

Figure 35 Temperature contours at a section through the centre of the tunnel at 10 minutes

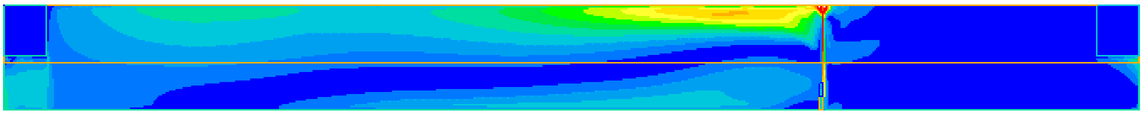

Figure 36 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX F CFD RESULTS – NATURAL VENTILATION – RUN 5

Figure 37 Temperature contours at a section through the centre of the tunnel at 1 minute

Figure 38 Velocity contours at a section through the centre of the tunnel at 1 minute

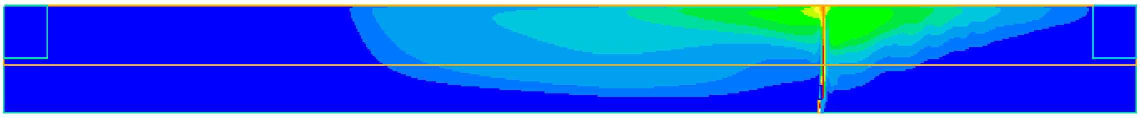

Figure 39 Temperature contours at a section through the centre of the tunnel at 5 minutes

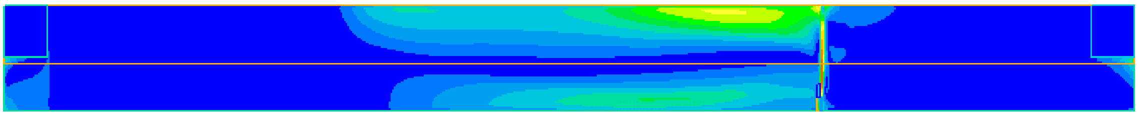

Figure 40 Velocity contours at a section through the centre of the tunnel at 5 minutes

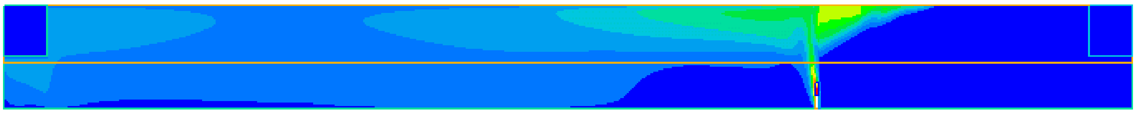

Figure 41 Temperature contours at a section through the centre of the tunnel at 10 minutes

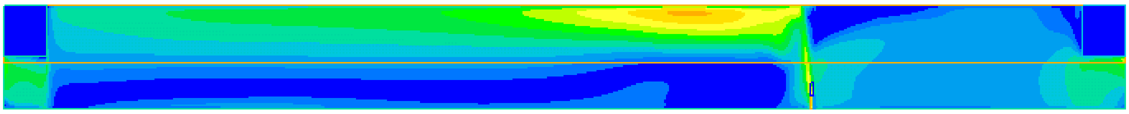

Figure 42 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX G CFD RESULTS – NATURAL VENTILATION – RUN 6

Figure 43 Temperature contours at a section through the centre of the tunnel at 1 minute

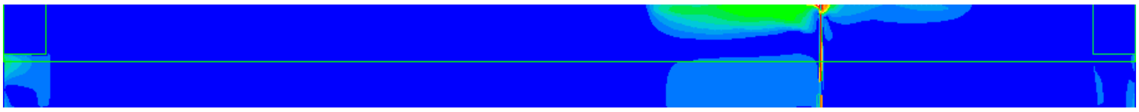

Figure 44 Velocity contours at a section through the centre of the tunnel at 1 minute

Figure 45 Temperature contours at a section through the centre of the tunnel at 5 minutes

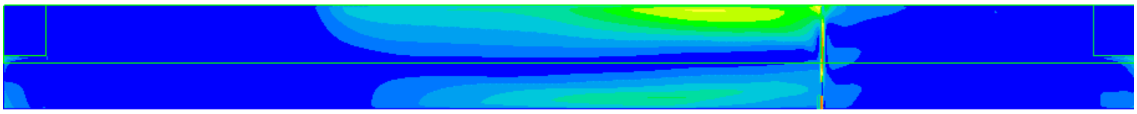

Figure 46 Velocity contours at a section through the centre of the tunnel at 5 minutes

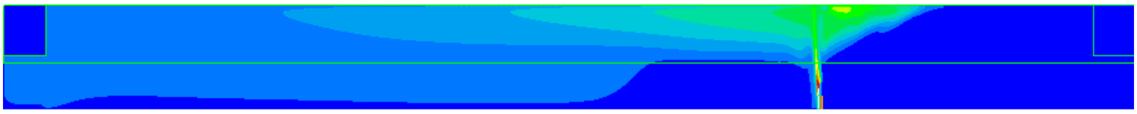

Figure 47 Temperature contours at a section through the centre of the tunnel at 10 minutes

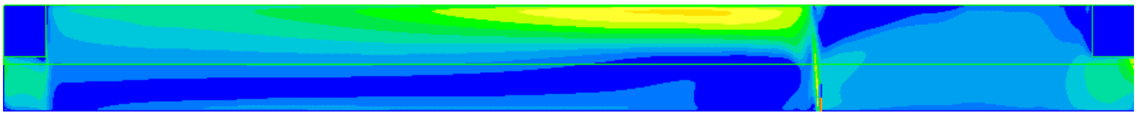

Figure 48 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX H CFD RESULTS – NATURAL VENTILATION – RUN 7

Figure 49 Temperature contours at a section through the centre of the tunnel at 1 minute

Figure 50 Velocity contours at a section through the centre of the tunnel at 1 minute

Figure 51 Temperature contours at a section through the centre of the tunnel at 5 minutes

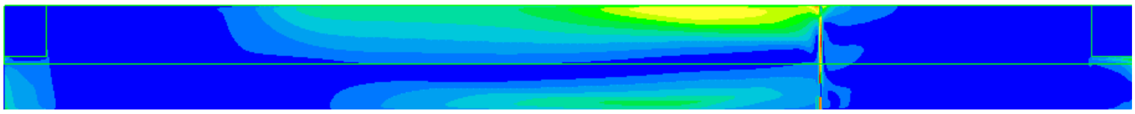

Figure 52 Velocity contours at a section through the centre of the tunnel at 5 minutes

Figure 53 Temperature contours at a section through the centre of the tunnel at 10 minutes

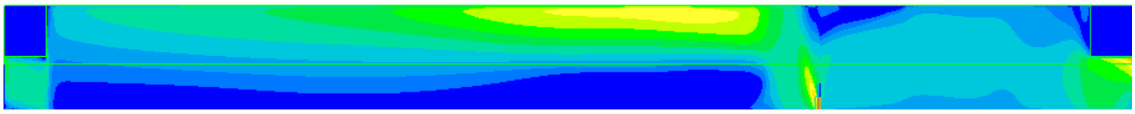

Figure 54 Velocity contours at a section through the centre of the tunnel at 10 minutes

APPENDIX I CFD RESULTS – NATURAL VENTILATION – RUN 8

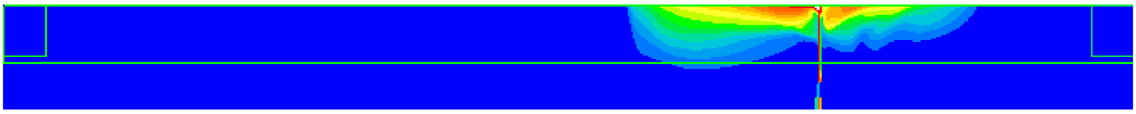

Figure 55 Temperature contours at a section through the centre of the tunnel at 1 minute

Figure 56 Velocity contours at a section through the centre of the tunnel at 1 minute

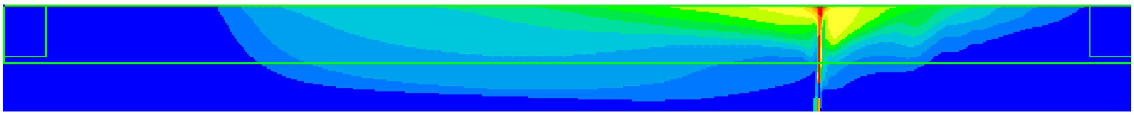

Figure 57 Temperature contours at a section through the centre of the tunnel at 5 minutes

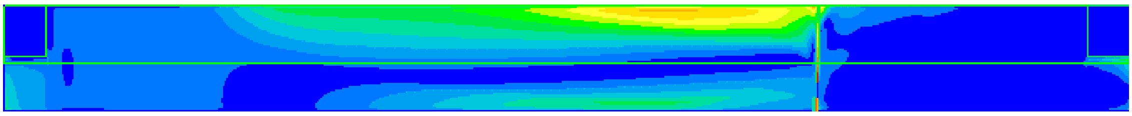

Figure 58 Velocity contours at a section through the centre of the tunnel at 5 minutes

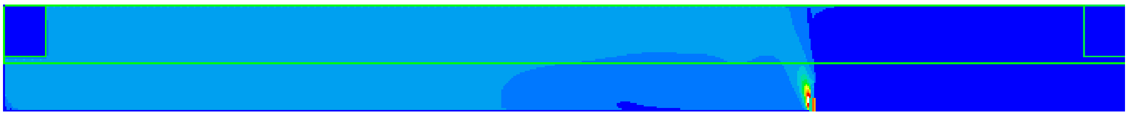

Figure 59 Temperature contours at a section through the centre of the tunnel at 10 minutes

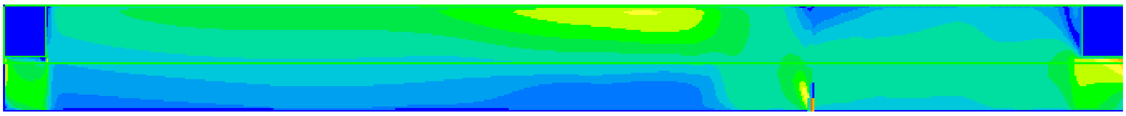

Figure 60 Velocity contours at a section through the centre of the tunnel at 10 minutes