TALLAWARRA B POWER STATION CFD PLUME MODELLING – GE-MODIFIED PDD DESIGN

SUMMARY REPORT

for Katestone

13TH AUGUST 2021

Ref 2001

REVISION HISTORY			
No.	**Date**	**Comment**	**Signed**
0	29th May 2020	Draft to Katestone	
1	22nd June 2020	Revised draft in response to comments	
2	20th August 2020	Final version	
3	25th March 2021	Inclusion of Fluent version in section 2.1. Detailed information on polyhedral elements in section 2.3. Inclusion of specified turbulence parameter at boundaries in section 2.4 Detail of stack boundary condition in Table 6. Correction of axis description in Figure 9. Inclusion of plume edge definition in Section 4.	
4	1st June 2021	Update to incorporate two additional simulations with calm wind condition	
5	15th June 2021	Revised draft in response to comments	
6	13th August 2021	Final version	C Stacey

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EXECUTIVE SUMMARY

Stacey Agnew has been engaged to undertake a detailed 3-dimensional (3D) computational fluid dynamics (CFD) analysis of the stack plume generated by the Tallawarra B Power Station. The high vertical flow and temperature of the plume has a big impact on the atmospheric flow around the stack, and the high vertical velocities in the plume can affect aircraft. It is desired to limit the plume rise velocities by adopting a stack-top diffuser.

This report covers the CFD plume modelling of the modified stack-top diffuser design proposed by General Electric. Geometric parameters and outlet conditions were provided by Katestone and are based on the specifications given by General Electric.

The applied methodology and wind conditions of the initial case are based on the CFD validation study already undertaken [10]. In addition to the 'initial' wind case, further investigations have been undertaken to analyse the plume behavior under calm wind conditions.

Katestone has provided the following details to Stacey Agnew for incorporation into the CFD model:

- Geometric parameters of the stack and plume dispersion device (PDD)
- Stack flow parameters and outlet conditions
- Meteorological data
- Atmospheric Boundary Layer (ABL) parameters

Based on these input data and depending on the examined wind conditions, the analysed PDD (modified design from General Electric) shows a total vertical plume rise of up to 1100 m (3609 ft) and a horizontal plume displacement of up to about 360 m (1181 ft). These extents refer to the region within which the maximum plume velocity might exceed ambient wind conditions.

In this assessment the plume area is defined as the horizontal area over which the vertical plume velocity exceeds a specific value. This has been done for four different plume rise velocity criteria (areas over which the vertical plume velocity exceeds 6 m/s, 4 m/s, 2 m/s and 1 m/s). At an elevation of 200 m (about 650 ft) the peak plume rise velocity is 11.9 ±0.4 m/s for the worst-case combined meteorological conditions (maximum of the three analysed cases). Depending on the plume area definition and the wind scenario, the average velocity at 200 m elevation is between 8.2 m/s and 3.5 m/s. This wide variation suggests that average velocity over an arbitrarily selected area may not be useful in assessing performance, and another measure should be sought.

In addition to the plume rise velocity analysis already undertaken, an equivalent TAPM 'top hat' profile velocity and radius has been identified for three different heights. This allows a comparison of the CFD results with the TAPM model results, and with criteria based on TAPM outputs. Table 1 summarises the equivalent top hat profile values for the heights and wind cases examined.

The individual jets released by the PDD are mainly affected by the density deficit and therefore by the buoyancy force within the first 50 to 100 m (164 to 328ft) in elevation. Above this initial plume region, the wind speed and direction become more relevant in the plume shape and displacement. The analysis of the different wind scenarios showed that, depending on the ambient temperature, the individual vertical plume jets can either attach to each other or stay separate. Once the jets are combined to a single vertical jet (lower ambient temperature) the maximum plume rise velocity can reach a value of up to 12.3 m/s.

Higher wind speeds above 100 m (328 ft) disturb the plume shape more, which results in slightly lower peak velocities.

Table 1. Summary of equivalent top hat profile values for different heights.

Plume definition	Unit	650 ft	700 ft	1000 ft
'Initial' wind case (20140703_10)				
Equivalent top hat velocity (u)	m/s	5.5	4.9	3.9
Equivalent top hat radius (R)	m	58.6	69.4	114.3
Max. plume rise velocity from CFD	m/s	11.5	11.5	10.7
Calm wind case (20150308 – Calm)				
Equivalent top hat velocity (u)	m/s	4.1	4.1	3.7
Equivalent top hat radius (R)	m	81.9	84.8	111.0
Max. plume rise velocity from CFD	m/s	8.4	8.1	7.3
'Combined' wind case (Wind: 20150308 – Calm, Temperature: 20140703_10)[#]				
Equivalent top hat velocity (u)	m/s	6.7	6.6	6.1
Equivalent top hat radius (R)	m	46.6	49.3	65.2
Max. plume rise velocity from CFD	m/s	11.9 ±0.4	11.7±0.4	10.5±0.4

[#] Values are based on analysed timestep of a transient simulation. Fluctuations are observed over a period of about 20 minutes (see Figure 23).

Beyond the discussion of the relevant average plume rise velocity and the top hat profile equivalence approach in Section 4, CASA stated in their letter [12] that they will accept half of the peak plume rise velocity as measure for potential impacts on aircraft.

Table of Contents

1 INTRODUCTION

Tallawarra B is a gas fired power project comprising an open-cycle gas turbine plant (OCGT) designed to meet the electricity demand in the NEM. The OCGT units produce a large volume of hot exhaust gas that rises quickly into the atmosphere, generating updraughts with potentially high vertical velocities at high elevations. These updraughts and vertical velocities have potential to adversely affect aircraft flying in the vicinity of the stack.

To reduce vertical velocity or temperature of the plume, General Electric has offered for consideration a modified stack-top diffuser design. This report covers the CFD results only of the modified diffuser solution offered by General Electric. The geometric design parameters and stack outlet conditions were provided by the manufacturer.

A previous investigation covered a CFD validation study, of a simple circular stack and defined boundary conditions that are applicable to the power station. These results were documented in a separate report [10].

The simulation methodology and wind conditions for this study are adopted from the CFD validation study already undertaken.

2 METHODOLOGY

The simulation methodology used for this CFD study is based on the CFD validation case, summarised again as below.

2.1 Simulation Software

Tallawarra B Power Station plume modelling was carried out using the CFD-software ANSYS Fluent (Release 2019 R3) [1], [2], [3]. Fluent is a commercial generic CFD software for modelling fluid flow, heat transfer and chemical reactions in complex geometries. Table 2 lists the CFD model parameters used.

Table 2. CFD model parameters.

Parameter	Description
CFD-method and solver	Pressure based, steady-state Reynolds-averaged Navier-Stokes (RANS) solver with a spatial discretisation method of 2nd order. A second order discretisation method was used in order to avoid numerical diffusion.
Turbulence model	Realizable k-ε model with scalable wall function [4], [5]. The Realizable k-ε was developed to more accurately predict the spreading rate of planar and round jets (involving all jet regions) and provides adequate performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation and recirculation [1], [2]. This turbulence model was used because of the anticipated flow behaviour (jet flow at stack). A scalable wall function was used for the ground effects.
Thermal conditions	Ground surface was considered as flat, with a constant ground temperature according to the meteorological data provided [6]. The buoyancy effects of the hot smoke at the stack outlet are considered by using the incompressible ideal gas law and solving the energy equation rather than using the Boussinesq approach. The former approach determines the air density via the ideal gas law at a defined operating pressure, whereas the latter considers the buoyancy forces in the momentum equation where the density is determined via the thermal expansion coefficient β and a constant operating temperature T_0. The Boussinesq approximation eliminates the density from the buoyancy term and is only valid as long as changes in actual density are small $\beta(T-T_0) << 1$ [1].

2.2 Meteorological Conditions and Terrain

The meteorological input data for the validation case were provided by Katestone [6] and [7]. The following data were extracted from the 20140703_10 and 20150308 - Calm data set provided:

- Wind speed
- Wind direction
- Potential temperature (The temperature difference between a rising parcel of air and the adjacent ambient air)

Figure 1 illustrates the profiles of the applied atmospheric boundary layer (ABL). The plume rise has initially been analysed for the meteorological conditions 20140703_10 as illustrated in Figure 1. These conditions were selected from the TAPM modelling output that resulted in the 99.9th percentile plume average vertical velocity at 700 ft. Based on this initial study and CFD results, a further wind case with rather calm wind conditions has been analysed, to assess the sensitivity of the plume behavior and the maximum plume rise velocity. A calm wind was defined by Katestone as being less than 0.5 m/s.

Figure 2 shows the segment of occurring wind direction relative to the domain orientation for both wind cases. Depending on the height, the wind direction for the 'initial' wind case (20140703_10) changes from NNE (7°) to SSW (212°) and the wind speed from 0.5 to 6 m/s (2000 m above ground level). The wind profile for the calm wind case (20150308 – Calm) changes direction from NNE (17°) to W (272°) and the wind speed from 0.1 to 3.8 m/s as the elevation changes from 0 to 2000 m (0 to 6562 ft) above ground level. At around 210 m (about 700 ft), the wind speed is less than 0.5 m/s. In both wind cases, the potential temperature increases with height, which relates to a stable atmosphere. The domain orientation (as shown in Figure 2) was chosen to suit each wind profile so that the majority of the wind directions are captured with the inlet boundary conditions and so the domain orientation is different for the two wind profiles.

Compared to the initial wind profile, the average ambient temperature (from ground level to 2000 m or 6562 ft) for the calm wind profile is 7.2°C higher. A change of 7.2°C in the ambient temperature seems very minor. However, it seems that calm wind case has very different results to the 'initial' wind case, so there was a need to understand the temperature and wind effects separately. To analyse the sensitivity of the plume rise velocity to the wind speed and the ambient temperature individually, a third wind case has also been assessed. This case combines the wind direction and speed of the calm wind case (20150308 – Calm) with the "cooler" temperature profile of the 'initial' wind case (20140703_10). The resulting three wind cases are summarised in Table 3 below.

Table 3. Wind cases used for the CFD-study.

<table>
<tr><th>Wind case</th><th>Wind profile</th><th>Temperature profile</th><th>Average ambient temperature</th></tr>
<tr><td>'Initial' wind case</td><td colspan="2">20140703_10</td><td>16.4°C</td></tr>
<tr><td>Calm wind case</td><td colspan="2">20150308 – Calm</td><td>23.6°C</td></tr>
<tr><td>'Combined' wind case</td><td>20150308 – Calm</td><td>20140703_10</td><td>16.4°C</td></tr>
</table>

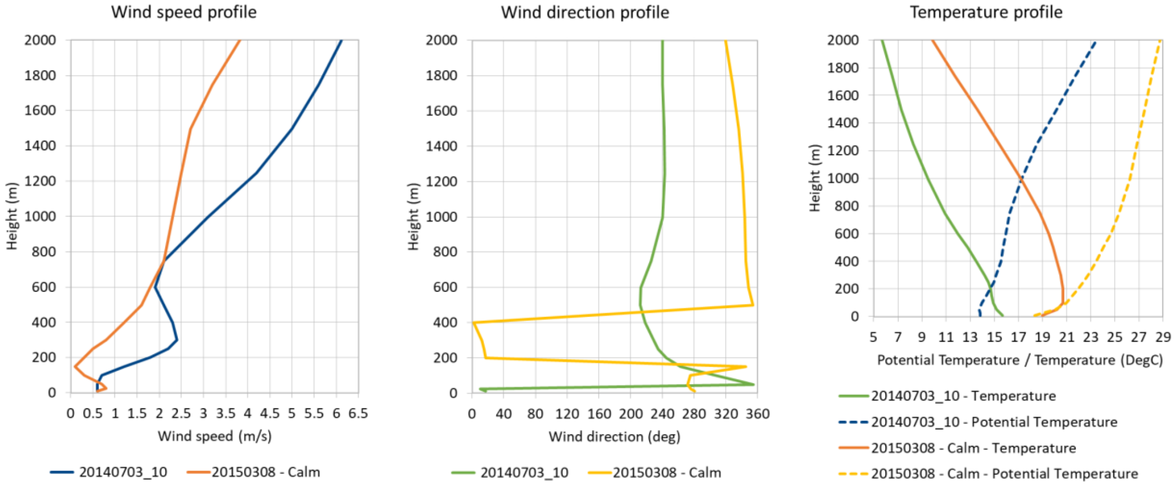


Figure 1. Profiles of wind speed (left), wind direction (middle) and temperature (right) used for the assessment [6], [7].

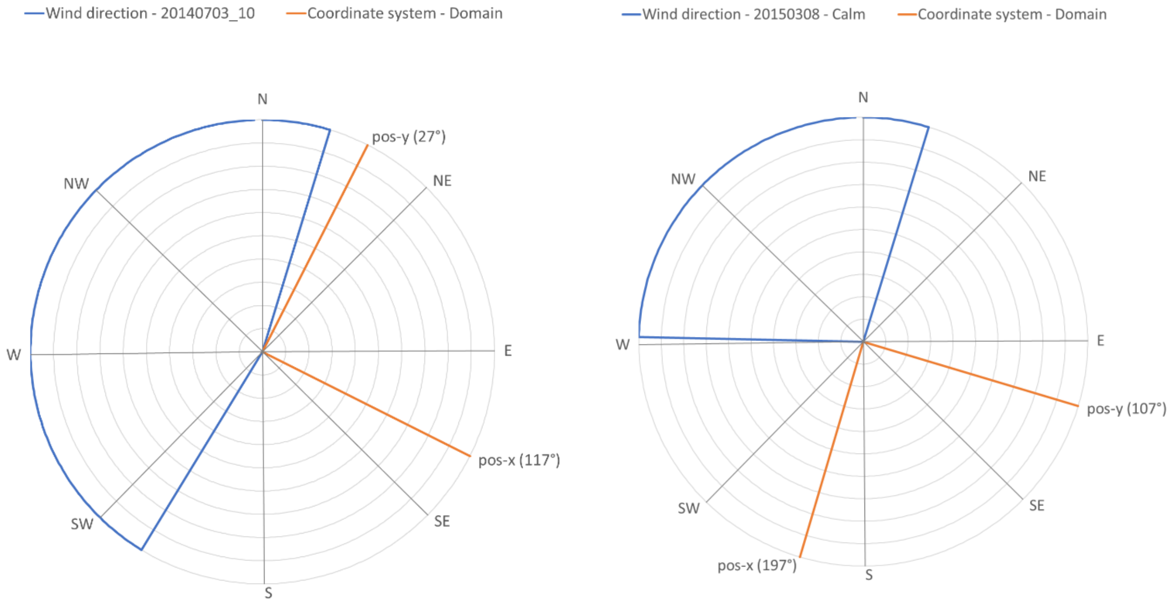


Figure 2. Segment of occuring wind direction (blue) and cooridnate system of the computational domain (orange) for the 'initial' (left) and the calm (right) wind profile.

Figure 3 shows the terrain within an area of 34 × 34 km around the assessed site with a resolution of 1 km. As can be seen in Figure 3, the terrain around the power station within several kilometres is relatively flat (red circle). Because the domain for the CFD plume analysis is within the order of the terrain resolution, a flat terrain was used for the investigation. It was assumed that the terrain and surface influences were included in the velocity profile provided.

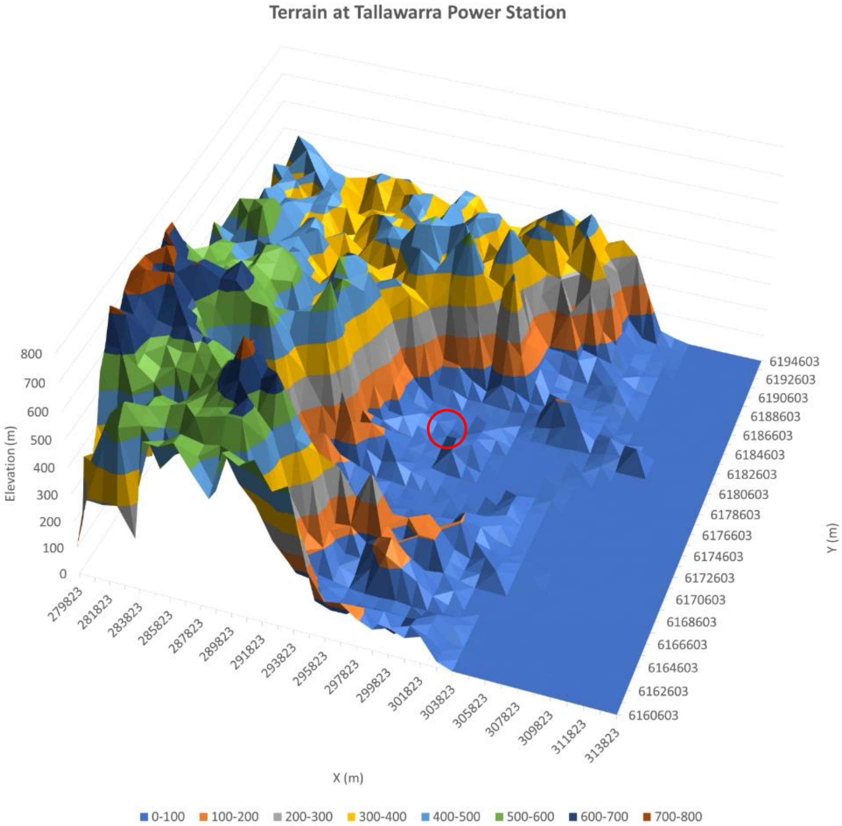


Figure 3. Terrain within an area of 34 km × 34 km around the site (resolution: 1 km).

2.3 Geometry and Computational Domain

Figure 4 depicts the computational domain and mesh for the plume modelling. An overall domain size of 2700 x 2700 m with a height of 2000 m was adopted so that the boundary conditions would have no significant influence on the simulated plume flow around the stack. Domain orientation for the two velocity profiles is illustrated in Figure 2. The stack was positioned in the middle of the domain (in x-direction) and 2000 m upwind of the outlet boundary condition (in y-direction). The station building was not modelled. The point of origin is at the stack centre at ground level. Table 4 lists the geometric stack and PDD parameters according to [8]. Figure 5 shows a sketch of the modified PDD.

Table 4. Geometric parameters of the PDD solution according to [8] .

Parameter	General Electric
PDD solution	modified
Stack X coordinate (m)	298,895
Stack Y coordinate (m)	6,177,812
PDD exit height above ground (m)	46.5
PDD outlet diameter (m)	-
PDD outlet dimensions (m)	1.83 x 1.38
PDD outlet area (m^2)	30.3
PDD outlet angle from vertical (deg)	90
PDD stack split number	12
PDD exit distance from stack CL (m)	5.6

The geometry was meshed with polyhedral surface elements in combination with hexahedral-core elements (see Figure 4). Polyhedral elements are only employed to connect the prism with the hexahedral elements in the direct proximity of the walls and boundaries. As shown in Figure 4, the remaining domain is discretised with hexahedral elements exclusively. To resolve the boundary layer at walls, prism elements were used. The maximum element sizes employed were as follows:

- outer domain surface (top, sides and ground): 10 m
- stack surface: between 0.8 and 0.4 m, and;
- global mesh size within the domain: 25 m.

A body of influence with a total height of 200 m was to create a fine mesh around the stack plume for enhanced resolution. Element sizes were defined based on distance away from the stack as follows:

- 0.1 m within the internal diffuser region and immediately outside,
- 0.6 m within the first 40 m, and
- 1.2 m within the following 120 m.

The resulting initial mesh had approximately 15 million elements

Based on this initial mesh, several mesh refinement steps within the plume region were undertaken so that the plume area was sufficiently resolved. The refinement steps and mesh resolution used were obtained from the mesh refinement study already undertaken during the validation case. The final maximum element size within the plume region was about 3.2 m. These parameters resulted in a mesh size with approximately 20 to 35 million elements.

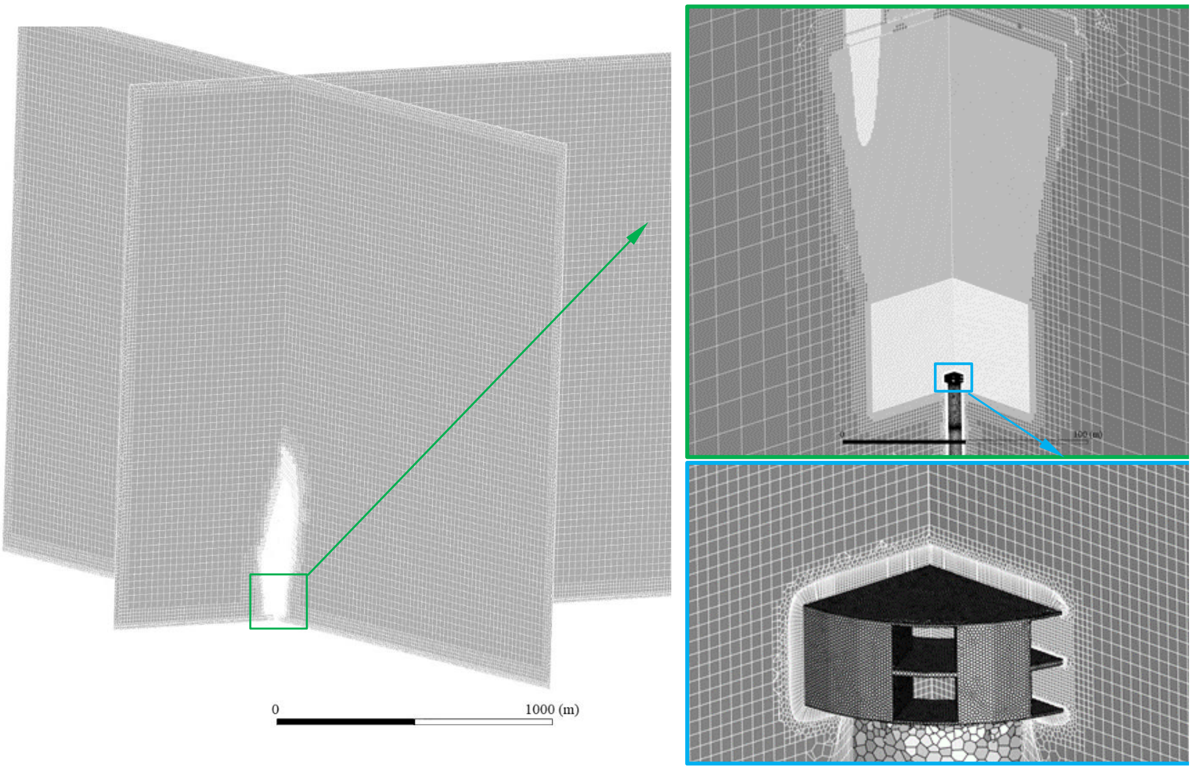


Figure 4. Computational mesh after several mesh refinement steps – Simulation with 'initial' wind case.

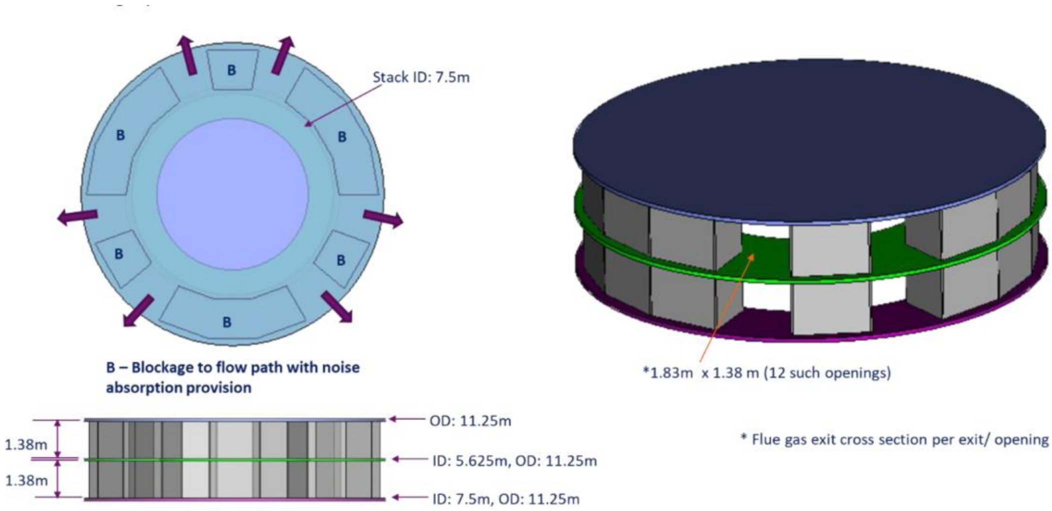


Figure 5. Sketch and dimensions of modified PDD solution proposed by GE [8].

2.4 Input Parameters and Boundary Conditions

The flow field around the stack is defined by the wind speed and temperature profile according to Figure 1. As the profiles of the ABL start at a height of 10 m, all values were extrapolated to the ground level. The wind direction and potential temperature were kept constant from 10 m to the ground, whereas the velocity was extrapolated by assuming 0 m/s and a roughness height of 0 m at ground level. The surface roughness has only a slight influence on the velocity profile below a relative elevation of 10 m. The stack flow parameters according to [8] are given in Table 5. Table 6 lists all applied boundary conditions for the plume modelling.

The velocity vector (based on wind speed and direction at different heights) of the analysed wind profiles was decomposed in its x- and y-components according to the domain orientation (see also Figure 2). These height-dependent velocity components were applied on the 'inlet' boundaries (velocity inlet as noted in Table 6). A positive velocity component at the inlet boundary means flow is going into the domain and a negative velocity component means flow is going out of the domain. This is a general practice in CFD and allows to capture all wind speeds and directions at the two inlet boundaries. The applied velocity and temperature profile changes the pressure field in the whole domain. To maintain the velocity and consequently the temperature field in the whole domain, the appropriate pressure profile has to be applied at the 'outlet' boundary (pressure outlet as noted in Table 6). Depending on the local pressure at the outlet boundary, flow can come into or going out of the domain, as such boundary conditions allow for backflows. The appropriate backflow conditions were specified (see also Appendix B). More comprehensive and specific information on the functionality of the inlet and outlet boundaries applied can be found in [1] and [2].

The turbulent intensity at the inlet boundary is specified as 5% and the turbulent viscosity ratio as 10. However, the specification of the turbulence parameters at the inlet boundary has insignificant influence on the plume behaviour as the boundaries are far away from the stack outlet and the turbulence parameters are developed within the domain, based on the velocity and temperature profile and their gradients.

In order to demonstrate the correct implementation of the boundary conditions as listed in Table 5 and Table 6, as well as to provide more information on the flow behaviour through the domain, additional contour plots and vertical velocity and temperature profiles are given in Appendix B

Table 5. Stack flow parameters [8].

Parameter	GE (modified PDD)
Average exit velocity at each nozzle outlet[1]	63.24 m/s
Total mass flow rate	746.0 kg/s
Exit temperature	633.7 °C

[1] Hand calculation based on opening/outlet area, total mass flow rate, exit temperature / density and an atmospheric pressure of 101.325 kPa.

Table 6. Boundary conditions for the validation plume modelling.

Location	Boundary condition
Two sides of the domain (negative x and y)	Velocity inlet with ABL (including wind direction and temperature) according to Figure 1 [6].
Two sides of the domain (positive x and y)	Pressure outlet with temperature profile according to Figure 1
Top of the domain	Wall with full slip condition and constant temperature of 23.4°C for wind case ‘20140703_10’ and 28.8°C for wind case ‘20150308 – Calm’ to maintain the velocity and temperature according to the corresponding ABL on the top of the domain.
Ground	Wall with fixed wall temperature of 13.9°C for wind case ‘20140703_10’ and 18.4°C for wind case ‘20150308 – Calm’ (surface roughness height $z_0 = 0.0\ m$)
Stack wall	Adiabatic wall
Stack outlet	Mass flow inlet (according to Table 5) applied down in the cylindrical stack as the internal nozzle and stack geometry is resolved (see Figure 4).

3 RESULTS

To analyse the plume velocity as well as plume temperature against height and downwind distance, two different plume trajectories were defined. The first trajectory was created by evaluating the maximum absolute plume velocity at different heights at 1 m intervals. The second trajectory was created by evaluating the maximum vertical plume velocity, also at different heights at 1 m intervals.

The following Sections 3.1 to 3.3 describe and evaluate the plume behavior for the 'initial' wind case according to Table 3 in detail. The results of the sensitivity cases are compared and discussed in section 3.4. Equivalent plots of plume velocity, extend and displacement as well as comprehensive contour plots as given in Sections 3.1 to 3.3 for the 'initial' wind case are also given for the sensitivity wind cases in Appendix A .

3.1 Plume Velocity and Temperature Against Height – 'Initial' Wind Case

Figure 6 shows the plume volume where the vertical plume velocity is > 6 m/s. The volume color refers to the plume height.

Figure 7 (left) shows the maximum vertical and absolute plume velocity against height as well as the atmospheric wind speed profile according to Figure 1. The maximum plume velocity reaches the ambient wind value at approximately 900 m (2953 ft) above the ground level. The maximum vertical plume velocity at this point is about 1.9 m/s. The plume temperature (right side of Figure 7) decreases rapidly with height and comes to within 0.5°C of the ambient value at about 750 m (2561 ft) above ground.

Figure 8 depicts the plume area against height (left) and the average plume velocities (right) within this area. Here the plume area is defined as horizontal area in which the vertical plume velocity is > 6 m/s. In addition, Figure 9 shows a similar plot and compares the plume area and average vertical plume velocity for different plume area definitions (area in which vertical plume velocity is > 6 m/s, > 4 m/s, > 2 m/s and > 1 m/s). Depending on the plume area definition, the average plume rise velocity varies between 8.2 m/s and 4.6 m/s at an elevation of 200 m (about 650 ft). Figure 11 illustrates the plume extent for the different vertical plume velocity criteria, based on value-clipped contour plots for vertical velocity.

The average vertical velocity and the plume area both vary dramatically with the choice of the vertical velocity taken as defining the plume edge. It is not clear whether any of the plume edge definitions gives a measure relevant to the effect on aircraft. It would seem that another measure not sensitive to the definition of the edge would be preferable.

In order to compare the CFD results with the TAPM model results and consequently with criteria based on TAPM outputs a different averaging method has to be used (see section 4).

The energy released by the stack is relatively large (high mass flow rate and temperature), which causes, in combination with the proposed PDD, an unusual jet flow behavior within the first 200 m (656 ft) in height. The stack exhaust is expelled in horizontal direction (90° to the stack) with a very high temperature. This high temperature (low density) generates high buoyancy forces, which turn the horizontal jets upwards to become a big vertical jet (requires about 40 m or 130 ft in height). As soon as the plume is vertical and joined together, the remaining plume temperature difference (low density) and therefore the buoyancy head is still high enough to further accelerate the plume from about 9 to 11.5 m/s (maximum plume rise velocity). This explains the increase in plume rise velocity from an elevation of about 100 to 200 m (328 ft to 656 ft). Due to the horizontal release of the plume, the vertical plume velocity within the first 20 m (66 ft) is much lower than the absolute velocity (Figure 8). Once the plume rises vertically, the maximum vertical and absolute plume velocity are very similar. Figure 10 illustrates the velocity and temperature distribution of the initial jet flow region.

The plots in Figure 7 to Figure 11 below are for the 'initial' wind case. Equivalent plots and pictures for the "calm wind case" and "combined wind case" can be found in Appendix A .

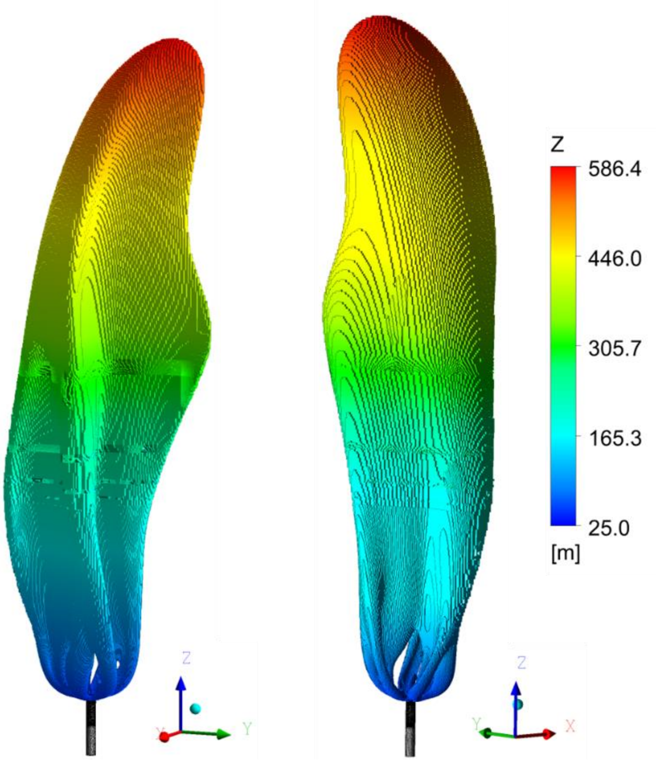


Figure 6. Plume volume where vertical plume velocity is > 6 m/s. Contour plot refers to the plume height - 'Initial' wind case.

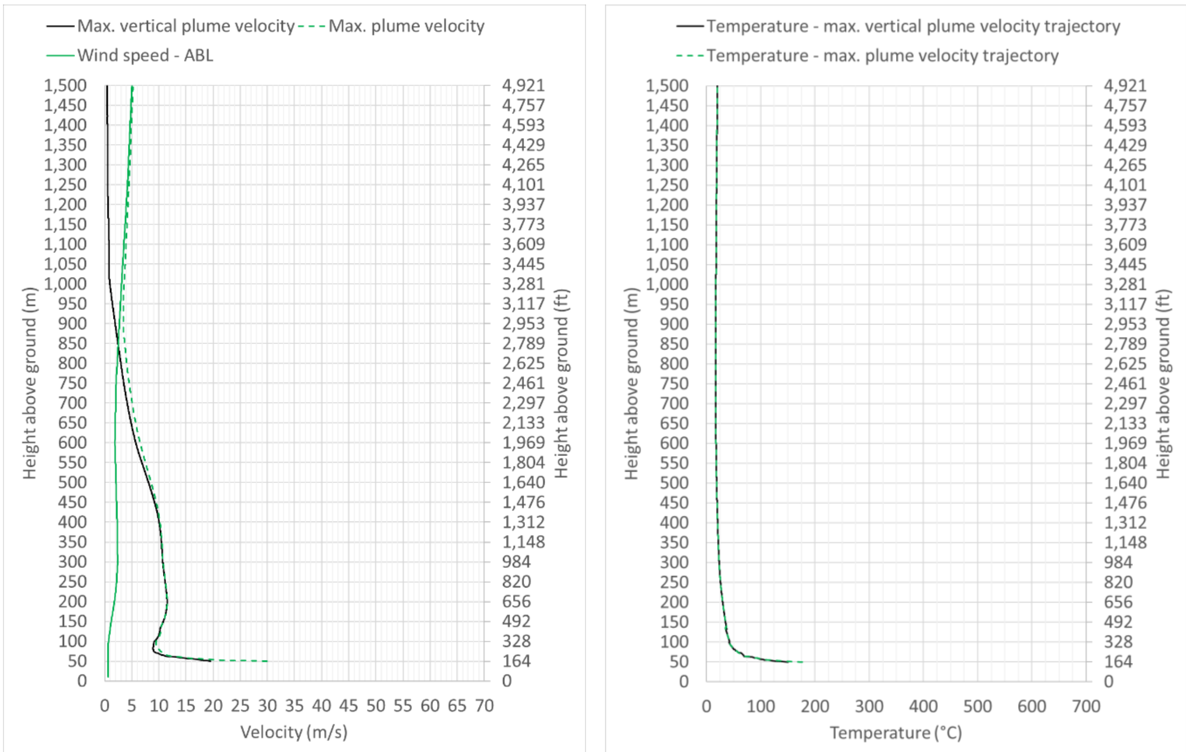


Figure 7. Wind speed and maximum vertical and absolute plume velocity against height (left) and plume temperature alonge both trajectories (right) – 'Initial' wind case.

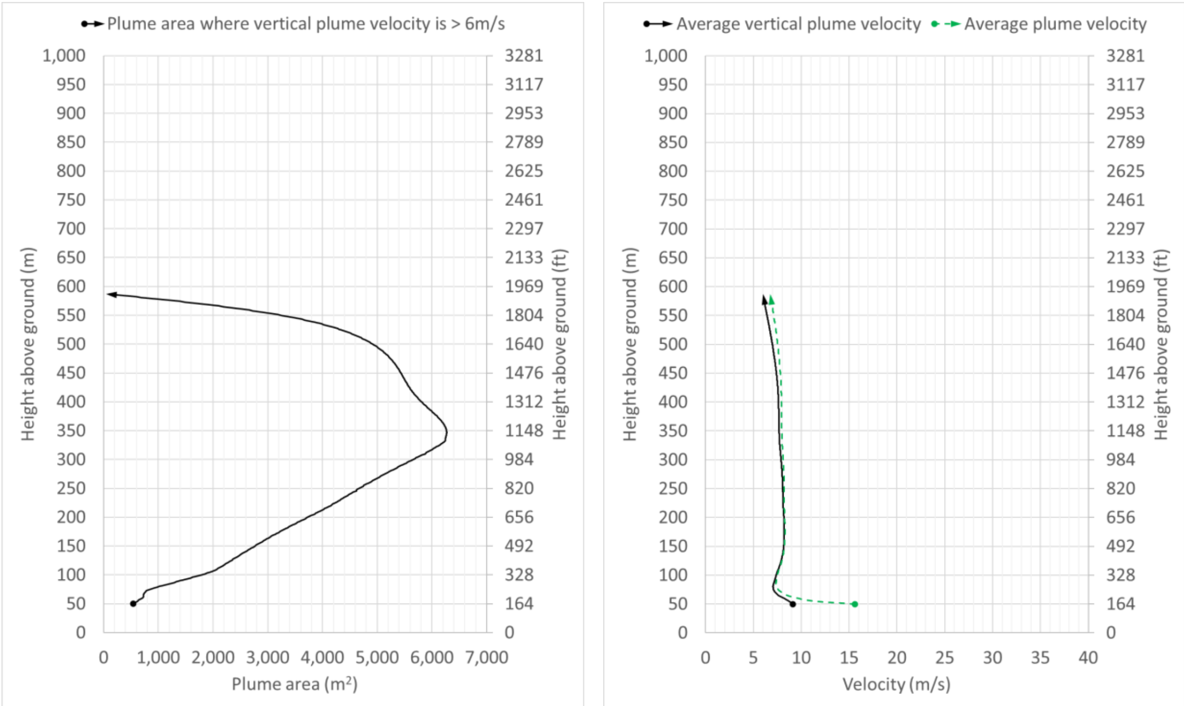


Figure 8. Plume area (area where vertical plume velocity is > 6 m/s) (left) and average plume velocities against height (right) – 'Initial' wind case. Note that with the definition of plume area as being where the vertical velocity exceeds 6 m/s, the average vertical velocity in the 'plume' clearly can't fall below 6 m/s.

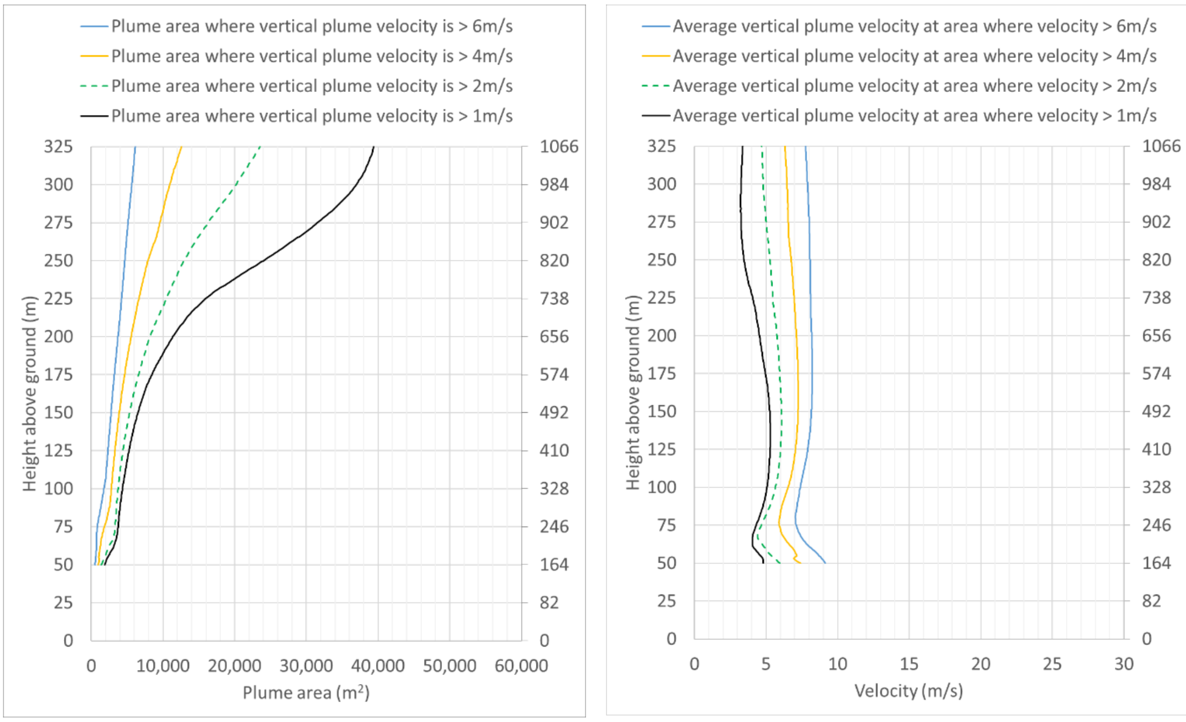


Figure 9. Plume area (left) and average plume velocities against height (right) for different plume area definitions – 'Initial' wind case.

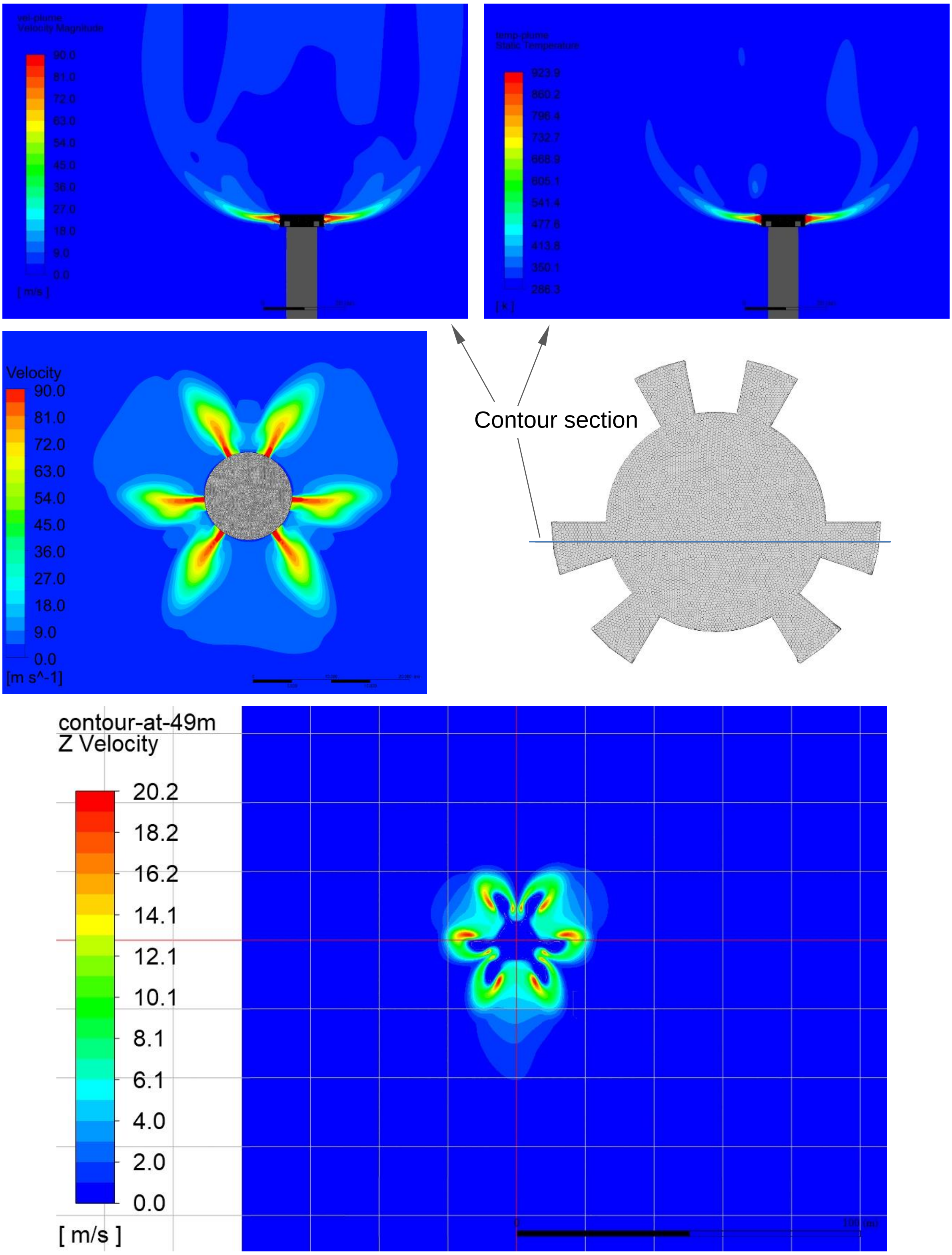
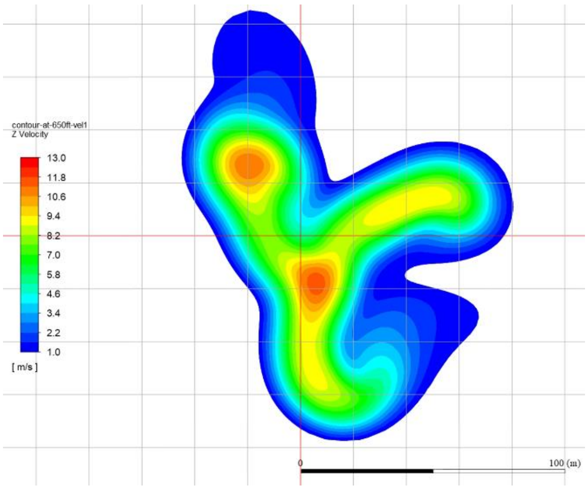
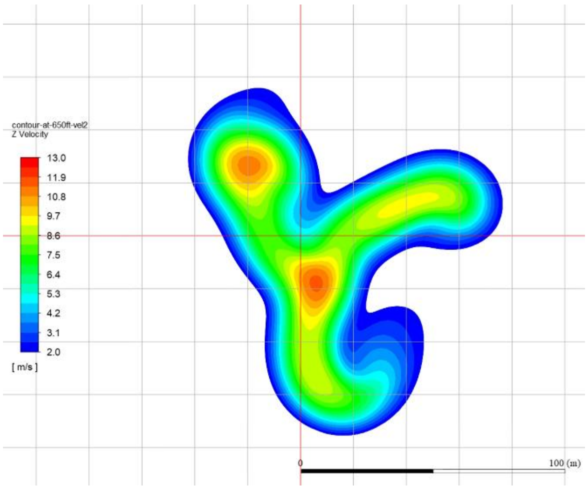


Figure 10. Contour of velocity (top left) and temperature (top right) close to the stack outlet as well as contour of velocity through the upper nozzle openings (middel) and about 2 m above the stack outlet in plane view (bottom) – 'Initial' wind case. Grid spacing in bottom picture is 20 m with stack centre at the origin.

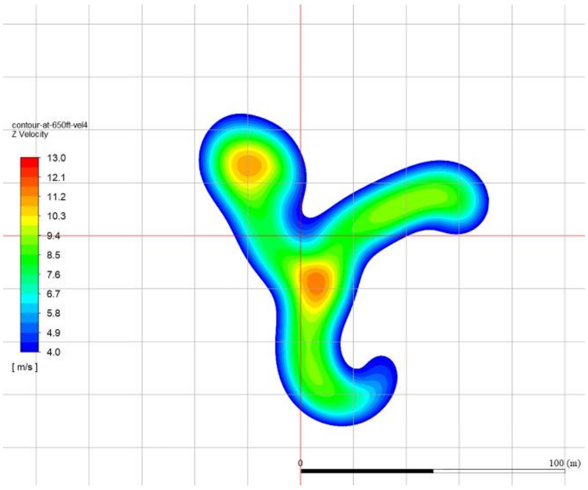
Vertical plume velocity > 1 m/s:



Vertical plume velocity > 2 m/s:



Vertical plume velocity > 4 m/s:



Vertical plume velocity > 6 m/s:

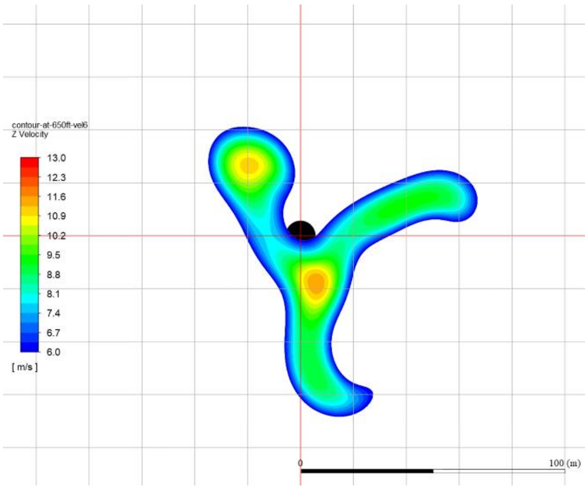


Figure 11. Plume extent shown as a contour plots of vertical velocity in a horizontal plane at 198 m (650 ft) elevation – 'Initial' wind case. The plume area in each contour plot is clipped to a different vertical plume velocity: > 6 m/s (bottom right), > 4 m/s (bottom left), > 2 m/s (top right) and > 1 m/s (top left). Grid spacing is 20 m with stack centre at the origin (red lines).

3.2 Plume Core Velocity Displacement – 'Initial' Wind Case

The growth in horizontal displacement of the locations of the maximum absolute plume velocity and maximum vertical velocity are very similar as illustrated in Figure 12. Once the plume core velocity nearly reaches ambient wind speed, the location of the maximum absolute plume velocity is sensitive to the local wind components. In this region, the location of the maximum absolute plume velocity can be slightly different to the location of the maximum vertical velocity. In general, the horizontal displacement of the plume is mainly caused by the applied wind conditions and will vary for different wind speeds and directions.

The coordinates are based on the domain, which means that positive y aligns with the direction NNE (27°). The maximum plume velocity reaches ambient wind conditions at an elevation of approximately 900 m (2953 ft) (where green lines join together, left plot in Figure 7). The maximum plume velocity varies with height between the several jets, which leads to the displacement jumps at lower elevation in Figure 12. The individual jets coalesce at an elevation of approximately 100 m (328 ft). The total horizontal displacement of the plume core is approximately 400 m (1312 ft).

Figure 13 shows the horizontal trajectory of the maximum vertical velocity component as well as the maximum absolute plume velocity in compass coordinates (abscissa towards North and ordinate towards East).

The plots in Figure 12 to Figure 13 below are for the 'initial' wind case. Equivalent plots and pictures for the "calm wind case" and "combined wind case" can be found in Appendix A .

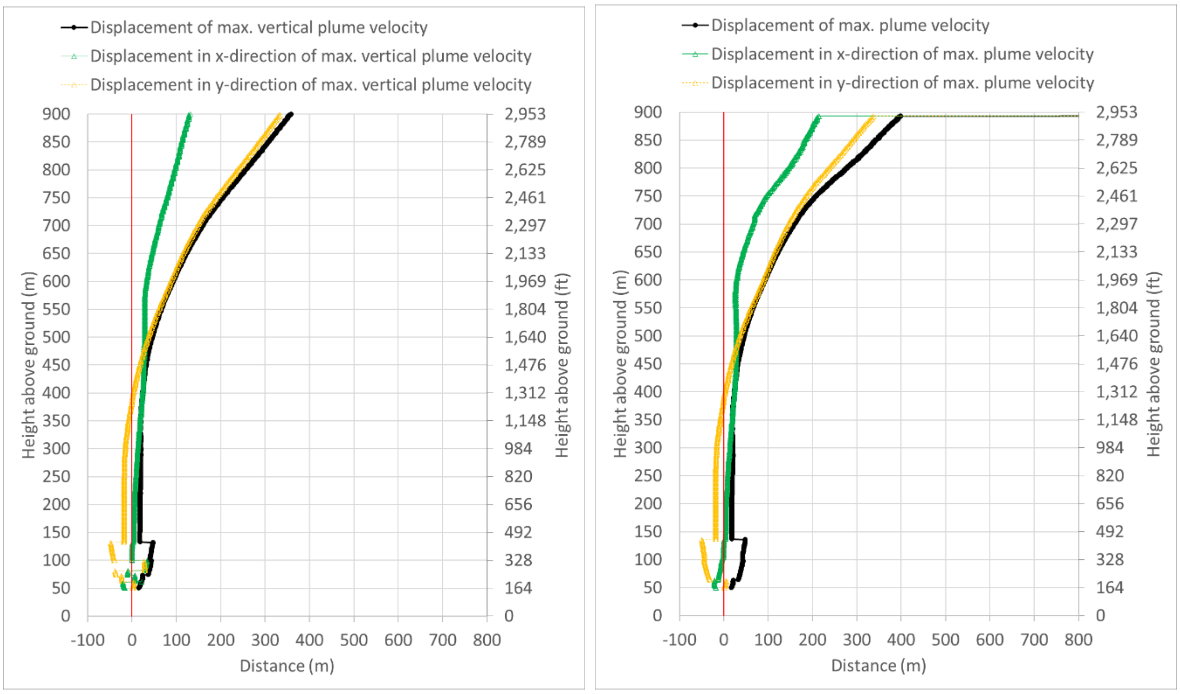


Figure 12. Displacement of maximum vertical velocity component (left) and of absolute core velocity (right) against height – 'Initial' wind case.

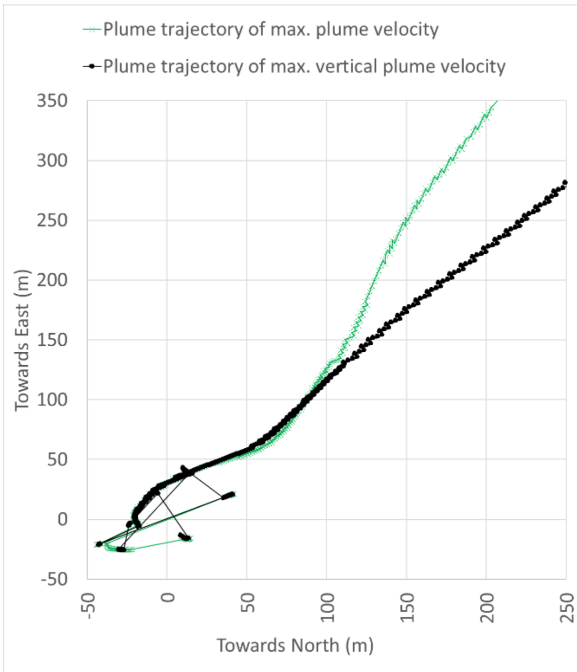


Figure 13. Horizontal trajectory of maximum vertical velocity and plume core velocity in compass coordinates – 'Initial' wind case.

3.3 Contour Plots – 'Initial' Wind Case

Figure 14 to Figure 18 depict contour plots of velocity magnitude, vertical velocity, and air temperature on x-z and y-z planes through the stack centre, or on horizontal planes at different heights. The black lines in Figure 16 to Figure 18 show the x and y planes through the stack centre. Contours are clipped for clarity.

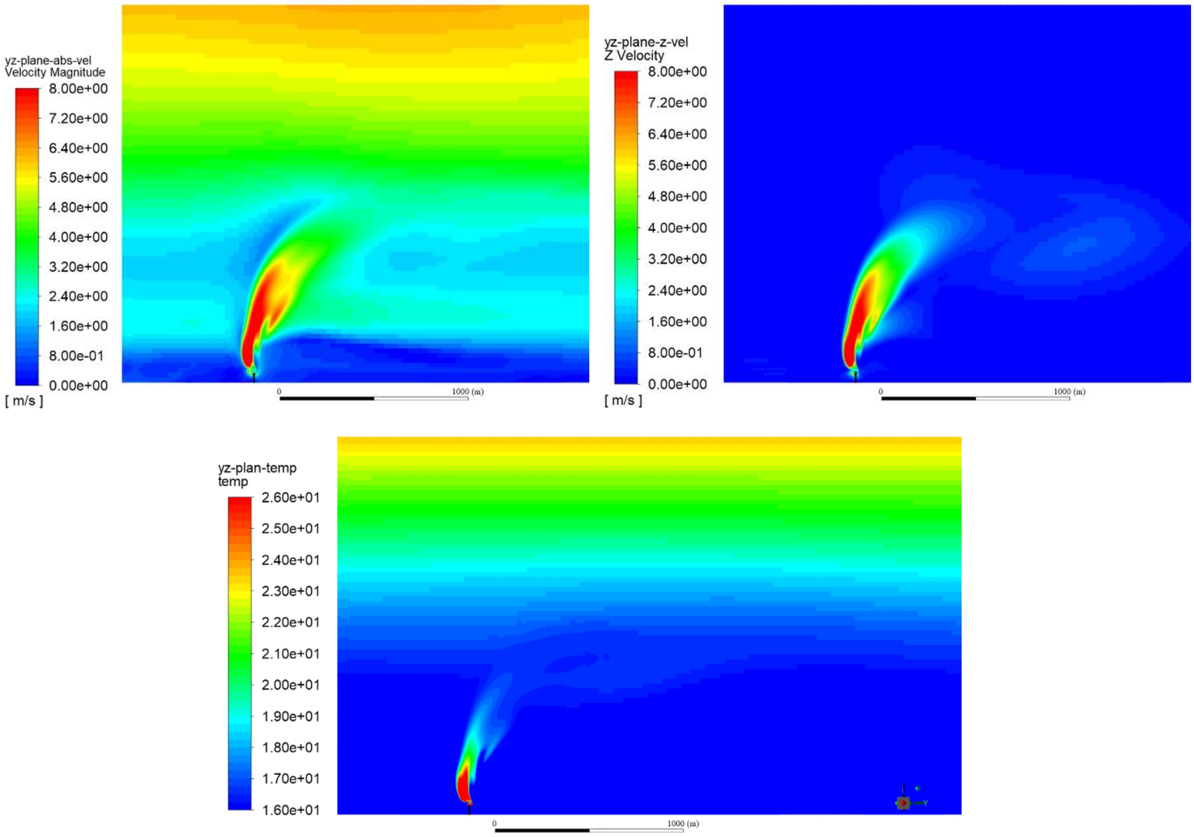


Figure 14. Contour plot in y-z plane through the stack centre for velocity magnitude (upper left), vertical velocity (upper right), and temperature (bottom) – 'Initial' wind case.

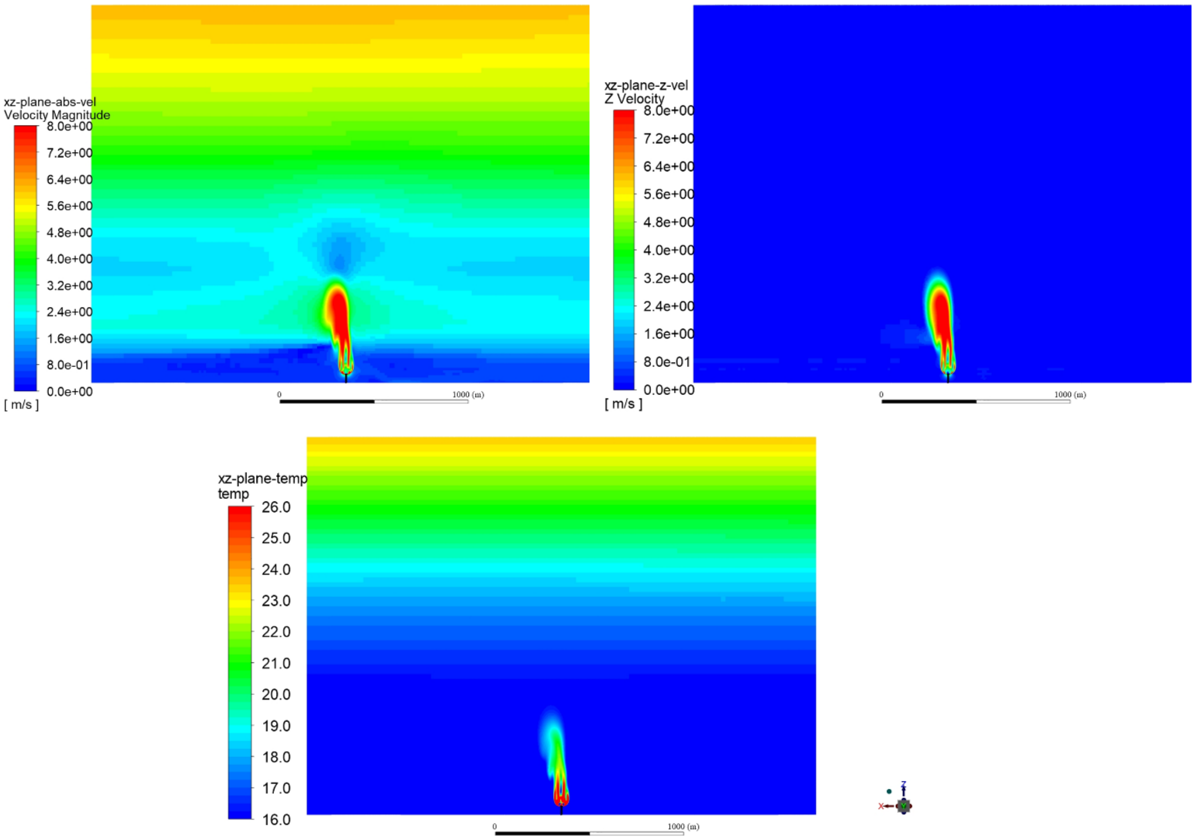


Figure 15. Contour plot in x-z plane through the stack centre for velocity magnitude (upper left), vertical velocity (upper right), and temperature (bottom) – 'Initial' wind case.

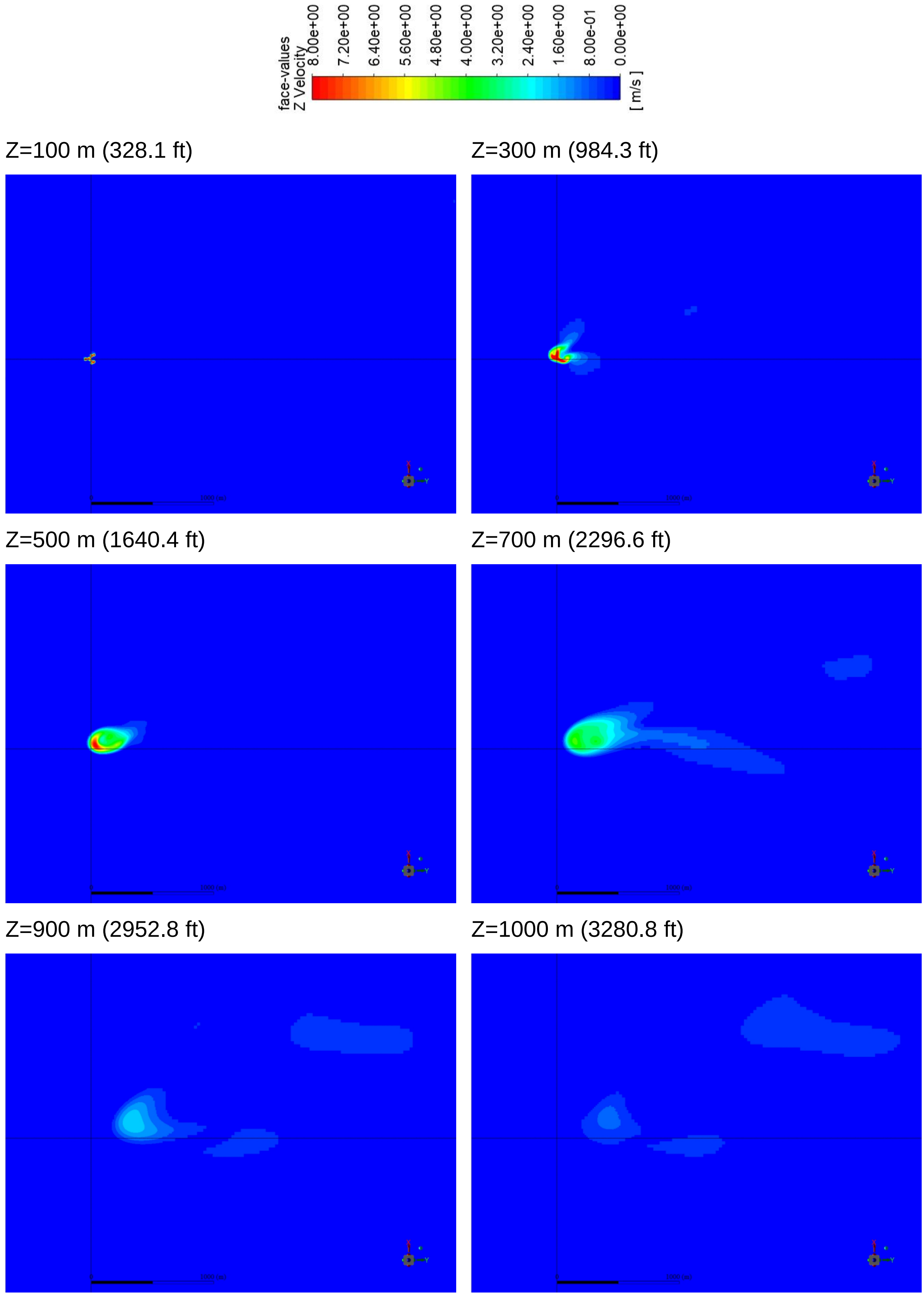


Figure 16. Contour plot of vertical velocity in plan at different horizontal plane heights – 'Initial' wind case. Black lines define the stack centre.

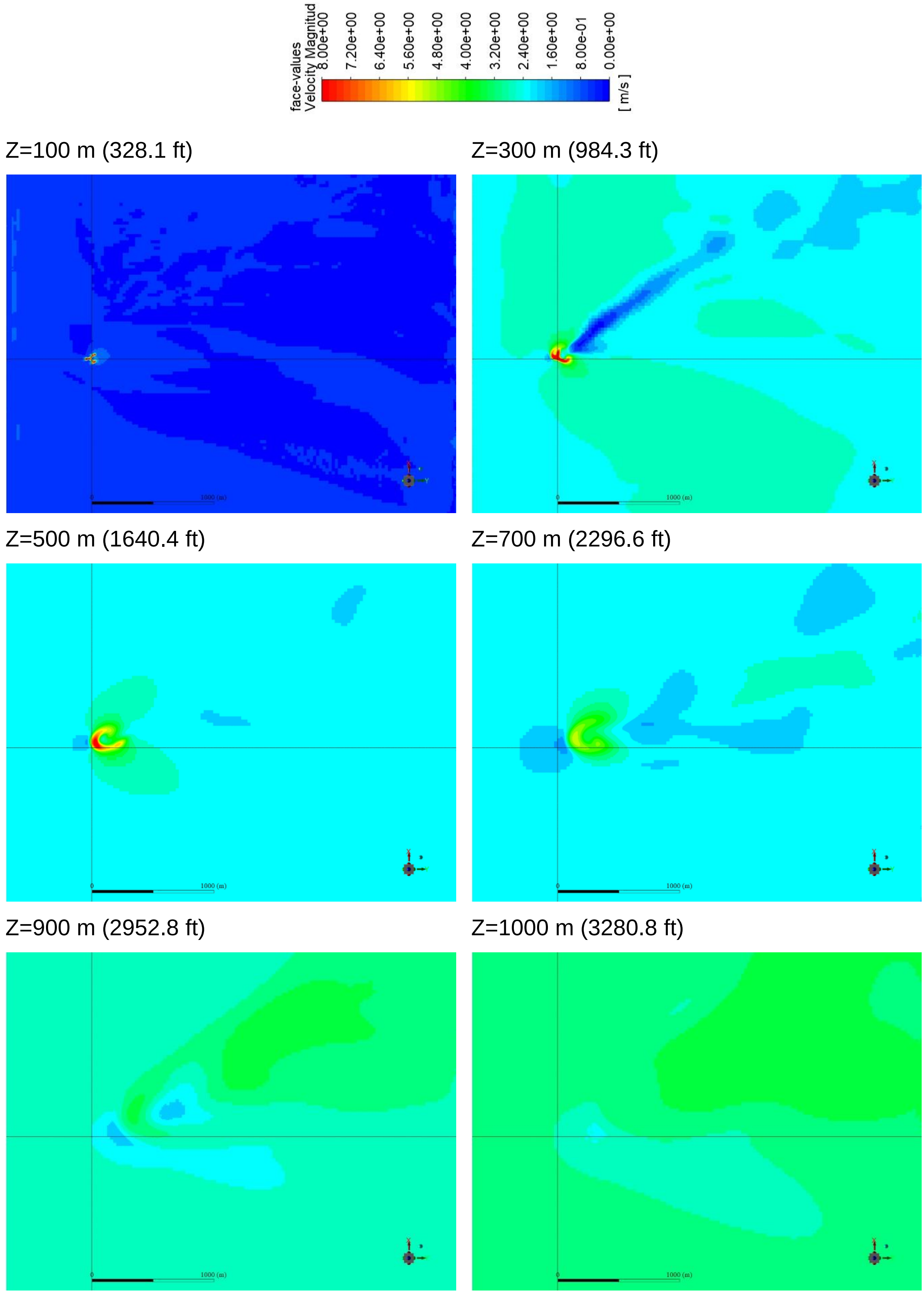


Figure 17. Contour plot of velocity magnitude in plan at different horizontal plane heights – 'Initial' wind case. Black lines define the stack centre.

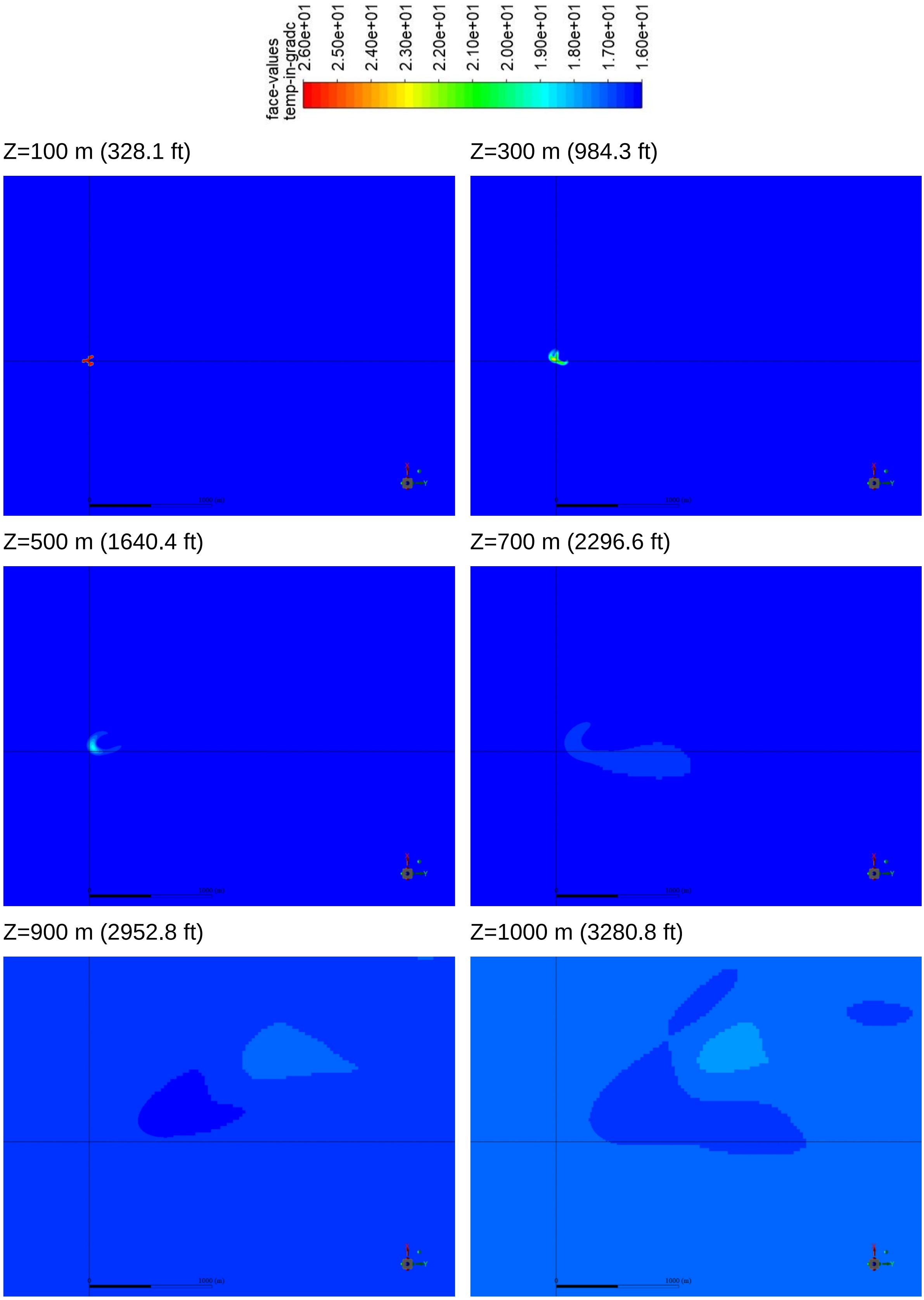


Figure 18. Contour plots of temperature in plan at different heights – 'Initial' wind case. Black lines define the stack centre.

3.4 Plume Behavior Sensitivity on Different Wind Conditions

As already mentioned, the nozzle design and corresponding detailed plume behavior was first analysed for the 'initial' wind conditions. These conditions were selected from the TAPM modelling output that resulted in the 99.9th percentile plume average vertical velocity at 700 ft. As the basis of a sensitivity analysis, the plume behavior with the same nozzle design, computational domain and stack parameter has also been assessed for a calm wind case. Compared to the 'initial' wind condition, the calm wind case has lower wind speeds but ambient average temperature that is higher by about 7.2 °C. The wind speed and direction impact the plume shape, entrainment, horizontal plume transportation and the natural plume convection, whereas the ambient temperature has an impact on the buoyancy force.

Figure 19 to Figure 22 below show the plume envelope for the different simulation cases, where the plume rise velocity is 6 m/s, as well as contour plots of absolute velocity, temperature and vertical velocity in a horizontal plan through the stack.

For the 'initial' wind condition, the released horizontal jets get bend upwards due to the density deficit and the resulting high buoyancy force. Similar to the Coanda effect, the now vertical jets tend to attach to each other, so that a single vertical plume jet is formed. The plume temperature in the core of the formed single jet is still high enough to further accelerate the plume rise velocity to a maximum value of 11.5 m/s (at 700 ft).

The higher ambient temperature (in average) for the analysed calm wind conditions reduces the buoyancy force and presumably the resistance acting on the ejected jet, so that the horizontal displacement of the individual jets is higher. It seems that, even though the input differences are slight, the increased displacement is enough that the individual jets (after they bend upwards) stay separated and do not form a single vertical jet. The core temperature in the single jets cools down faster due to the ratio between the plume volume and the plume surface interacting with the ambient air. The latter also causes higher flow resistance (shear stress) on the vertical jets. Both effects together result into much lower plume rise velocities with a peak value of 9.7 m/s at 400 ft. It is assumed that this plume behavior is rather unstable, and any disturbance which would cause to bring the individual jets closer together (e.g. lower ambient temperature which leads to higher buoyancy forces, lower exhaust mass flow or efflux velocity etc.), would result in a combined single vertical jet. Detailed analysis of the plume extents, displacement and velocities depending on the height, as well as further contour plots, can be found in Appendix A Section A.1.

Based on these results and observations, a further wind scenario with wind speed and direction from the calm wind profile (20150308 according to Figure 1) but with the lower ambient temperatures according to the temperature profile from the 'initial' wind conditions (20140703_10, according to Figure 1). The objective is to confirm the observations made and to see if the lower ambient temperature would lead to a single vertical jet . Corresponding results are shown, and compared to the previous simulation cases, in Figure 19 to Figure 22.

This 'combined' wind case confirms that the ambient air temperature has a meaningful influence on the plume behavior in general and the individual jets in particular. The buoyancy force at lower ambient temperatures is higher so that the individual jets bend upwards at an earlier stage. Therefore, the horizontal separation of the jets is lower and they are closer to each other once they are vertical. Similar to the simulation with the 'initial' wind case, the individual jets tend to attach to each other, so that a single vertical plume jet is formed again. The lower wind speed around the jets further helps to attach the individual jets, as the flow around and between the jets is lower (lack of air between the jets). Moreover, lower wind speeds reduce plume cooling, disturbance of the plume shape and natural convection as well as reduce the plume displacement in general. This leads to a slimmer and more vertical stretched single jet where the core temperature is slightly higher and more maintained. In turn, this leads to higher buoyancy forces and plume rise velocity, with a peak value of 12 m/s (+/- 0.4 m/s) at 590 ft.

The lower wind speeds on the natural plume convection led to quite high fluctuations of the monitored plume velocities (of +/- 0.4 m/s). This required a transient analysis of the plume. Based on a “steady state” solution, the flow field was analysed for a time period of about 20 minutes. For the detailed plume analysis, a time step where the plume rise velocity was close to the time average values has been chosen. Figure 23 illustrates the time-dependent peak velocity fluctuations at different heights, and the chosen time step. The monitored values are the maximum occurring velocity values within a horizontal plane cut through the whole domain. Detailed analysis of the plume extents, displacement and velocities depending on the height, as well as further contour plots of the evaluated time step can be found in Appendix A section A.2.

To demonstrate the transient behavior a video of the time dependent plume envelope is attached to this report. The envelope in the video is an iso-velocity surface at an absolute velocity of 8 m/s. Contour color depicts the plume height. Depending on the time, height and wind speed, jets detach and attach again, so that the plume rise velocity increases and decreases depending on the height (see Figure 37 in Appendix A section A.2.).

When comparing the plume envelope of the ‘initial’ wind case with the ‘combined’ wind case in Figure 20, it can be seen that the wind speed has minor impact in the jet formation but has more impact in the upper region where the plume velocities are much lower.

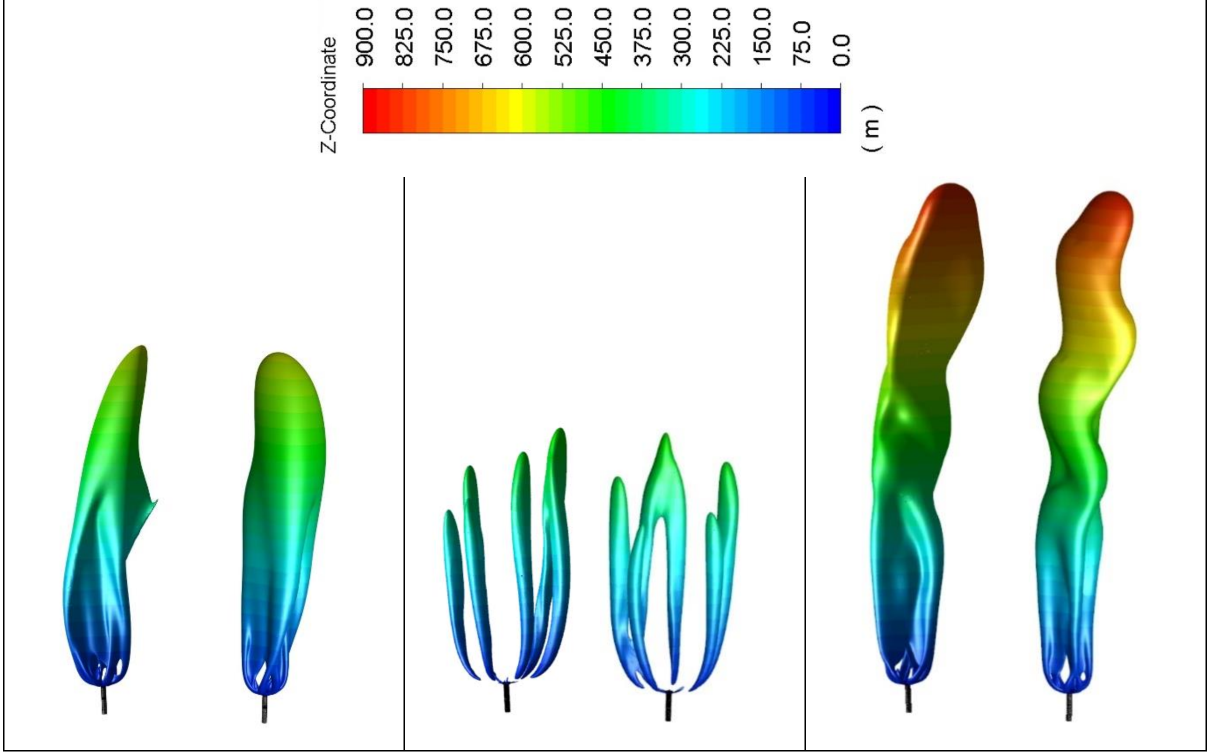
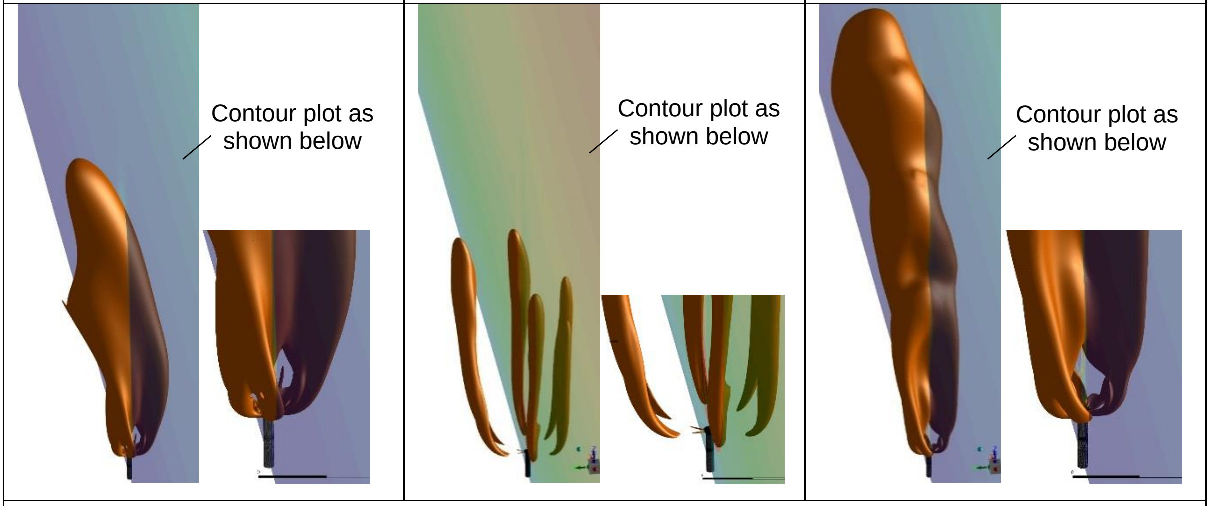
<table>
<tr><th>‘Initial’ wind case</th><th>Calm wind case</th><th>‘Combined’ wind case</th></tr>
<tr><td>Average ambient temperature: 16.4 °C
Initial wind profile</td><td>Average ambient temperature: 23.6°C
Calm wind profile</td><td>Average ambient temperature: 16.4 °C
Calm wind profile</td></tr>
<tr><td colspan="3">Plume envelope where vertical plume velocity is 6 m/s. Contour plot refers to plume height.
</td></tr>
</table>

Figure 19. Plume envelope where the plume rise velocity is 6 m/s for the different wind scenarios. Colouring of the envelope depicts the plume height.

‘Initial’ wind case	Calm wind case	‘Combined’ wind case
Average ambient temperature: 16.4 °C	Average ambient temperature: 23.6°C	Average ambient temperature: 16.4 °C
Initial wind profile	Calm wind profile	Calm wind profile



Contour plot of absolute velocity in plane through the nozzle as shown above

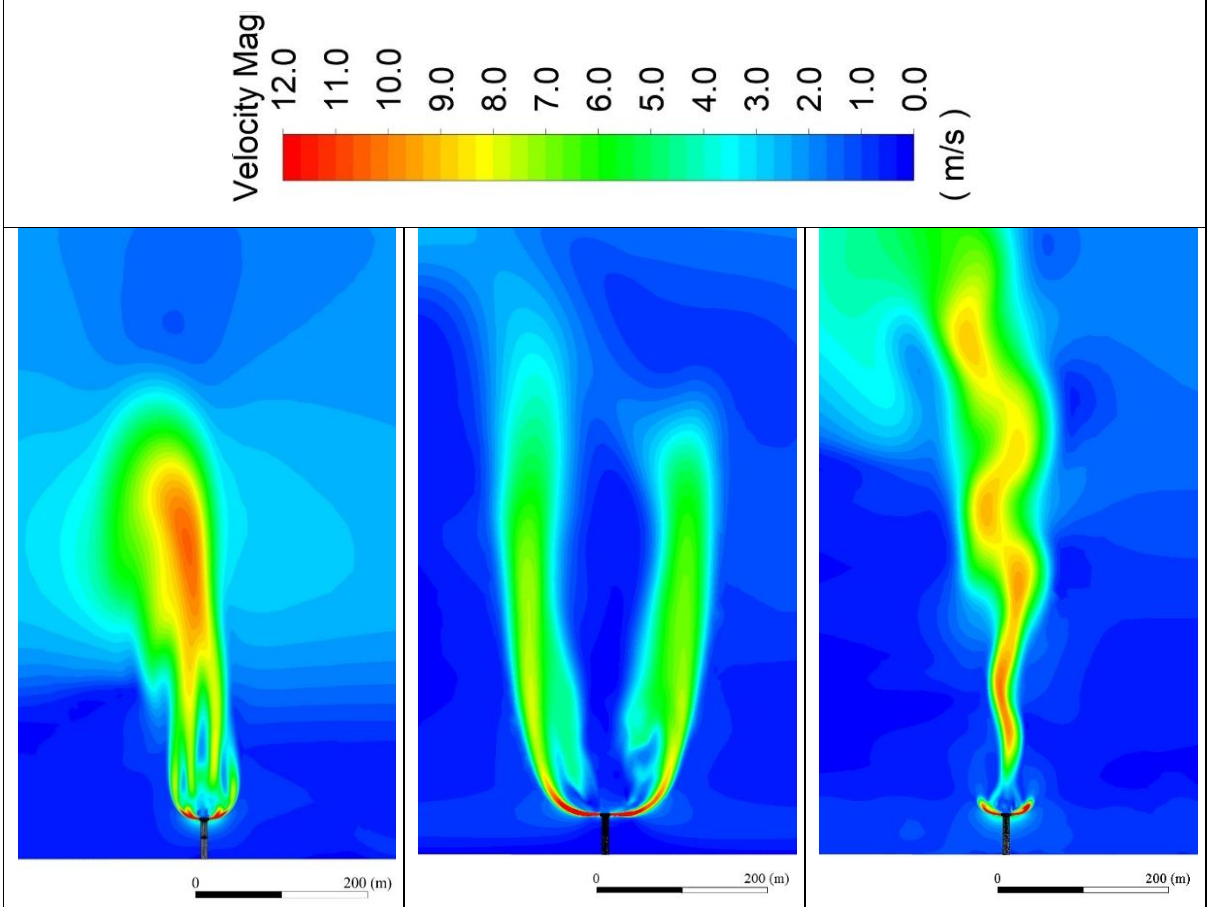


Figure 20. Plume envelope where the plume rise velocity is 6 m/s for the different simulation cases (top) and contour plot of absolute velocity in plane through the stack (bottom) for the different wind scenarios.

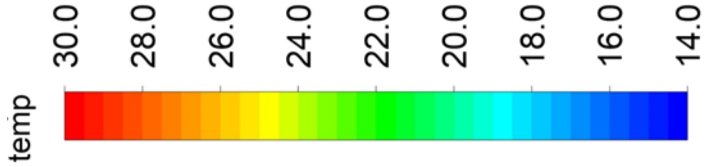
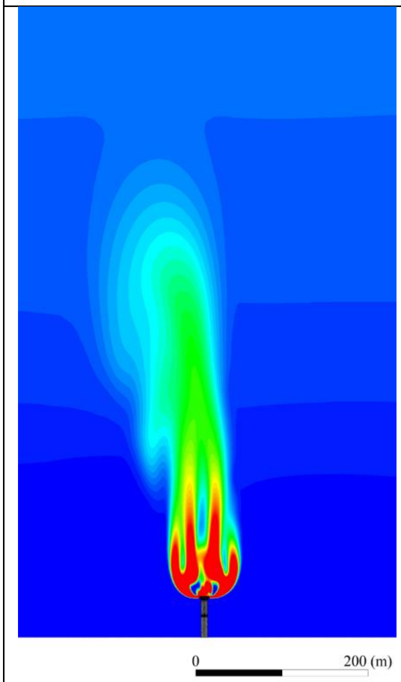
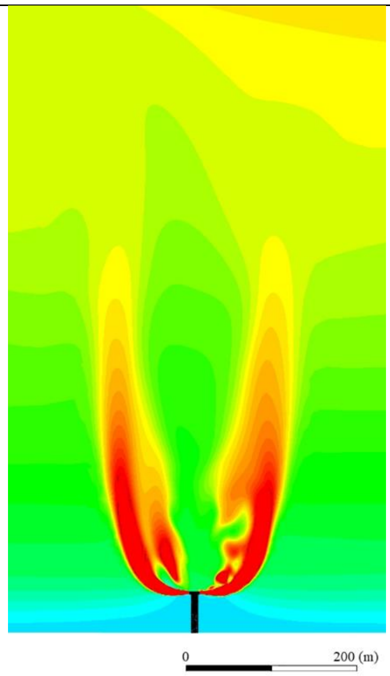
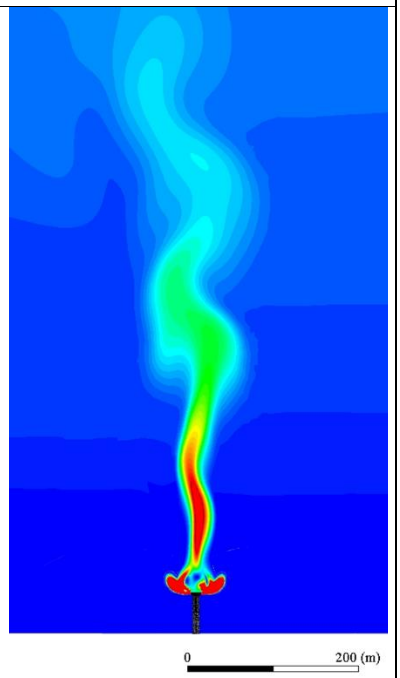
<table>
<tr>
<td>‘Initial’ wind case
Average ambient temperature: 16.4 °C
Initial wind profile</td>
<td>Calm wind case
Average ambient temperature: 23.6°C
Calm wind profile</td>
<td>‘Combined’ wind case
Average ambient temperature: 16.4 °C
Calm wind profile</td>
</tr>
<tr>
<td colspan="3">Contour plot of temperature in plane through the nozzle as shown in Figure 20
</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</table>

Figure 21. Contour plot of absolute velocity in plane through the stack for the different wind scenarios.

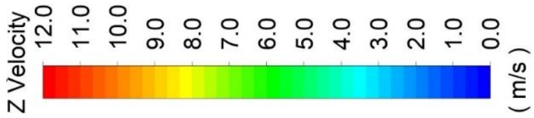
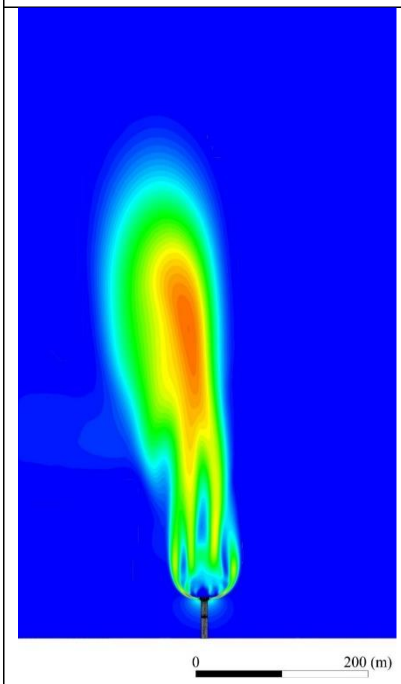
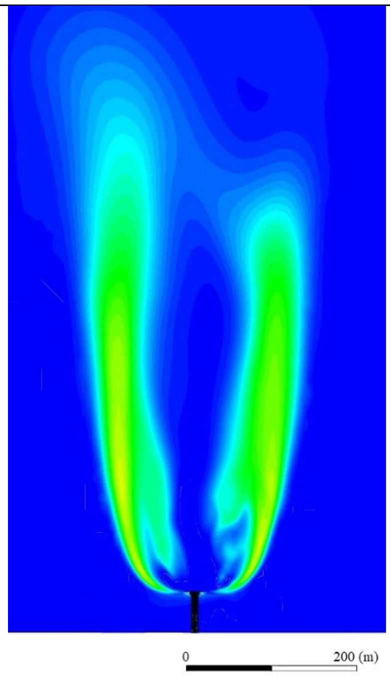
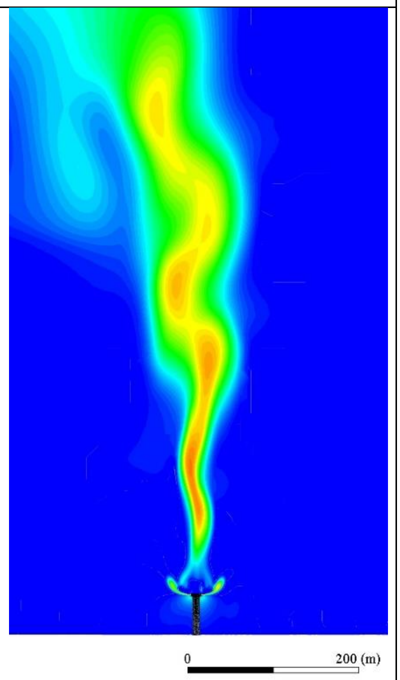
'Initial' wind case Average ambient temperature: 16.4 °C Initial wind profile	**Calm wind case** Average ambient temperature: 23.6°C Calm wind profile	**'Combined' wind case** Average ambient temperature: 16.4 °C Calm wind profile
Contour plot of vertical velocity in plane through the nozzle as shown in Figure 20 		
		

Figure 22. Contour plot of vertical velocity in plane through the stack for the different wind scenarios.

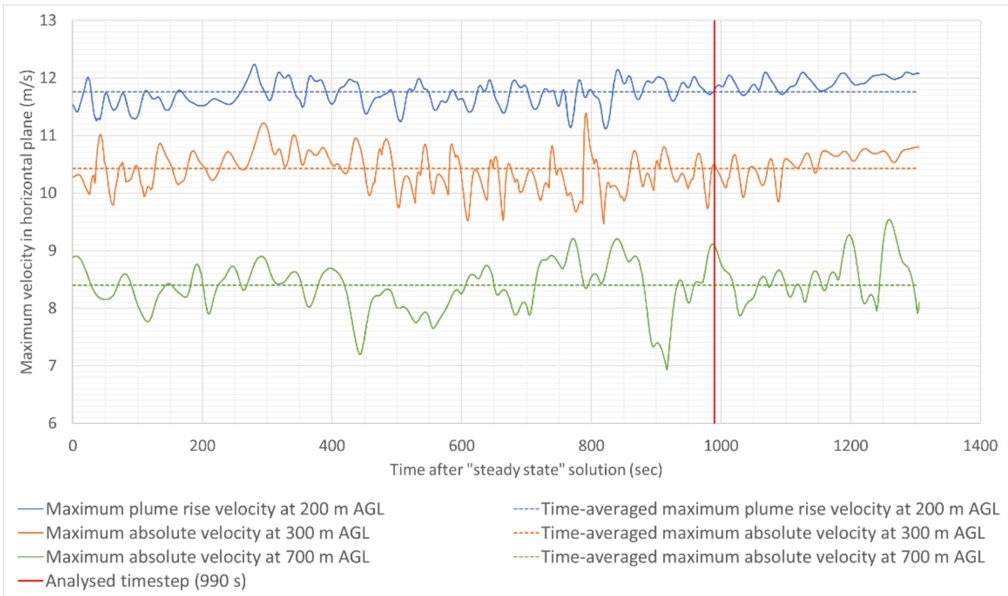


Figure 23. Monitored peak velocities at different heights depending on the simulation time and illustration of analysed timestep choosen for the detailed analysis of 'combined' wind case.

4 TOP HAT PROFILE EQUIVALENCE

The CASA plume rise velocity criterion is a single number refers to an average velocity resulting from TAPM. TAPM approximates the plume to a 'top hat' velocity in which there is only one velocity inside the plume, making the average velocity also the maximum. To compare the CFD results with the TAPM model results, an equivalent 'top hat' velocity needs to be determined.

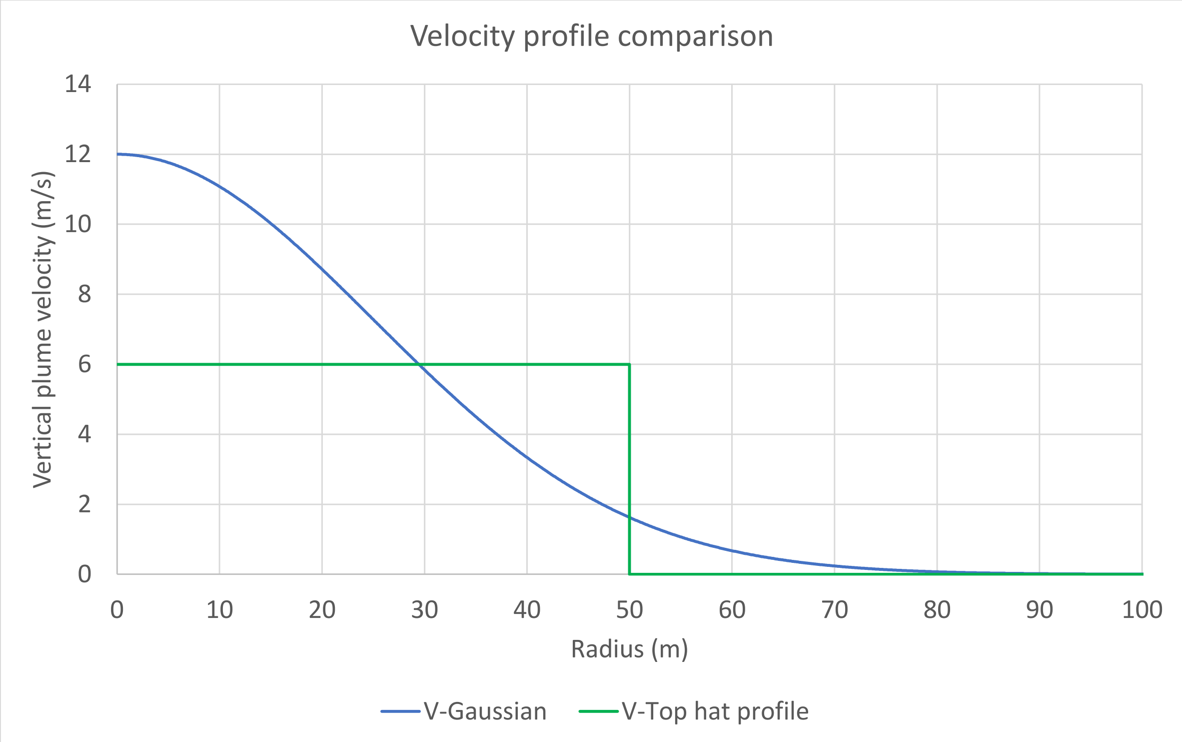


Figure 24. Velocity profile of a 'top hat', and a Gaussian distribution with a standard deviation of 25 m.

The average velocity and the plume spread in the TAPM model is based on a top hat profile. Those parameters are specified in such a way that the top hat profile seeks to match the momentum and flow rate of the real plume. When assuming that the vertical velocity profile of an individual plume has a perfect Gaussian distribution, the equivalent top hat radius is defined mathematically as being two times the Gaussian standard deviation, and the top hat velocity becomes half of the maximum velocity in the plume centre. However, the velocity profile of a plume released by a PDD does not have a Gaussian distribution. Depending on the wind conditions, the PDD design, the turbulence, the plume height, and the entrainment rate, this velocity profile can have several peaks and/or be asymmetrical. In order to determine an equivalent top hat velocity and radius based on the CFD results, it was assumed (as for the top hat and Gaussian profile correlation) that the flow rate and the momentum of the top hat profile matches those of the plume profile resulting from the CFD simulation. As the real velocity profile differs from a Gaussian distribution, the equivalent top hat velocity will no longer necessarily be half of the maximum velocity. The same divergence applies to the correlations for top hat radius and standard deviation. The analysis made here is mainly based on following assumptions and definitions:

Flow rate of top hat profile Q_{TH} to be matched with flow rate resulting from CFD simulation Q_{CFD} at specific height.

$$Q_{CFD} = Q_{TH} = u\,\pi R^2$$

Momentum of top hat profile M_{TH} to be matched with momentum resulting from CFD simulation M_{CFD} at specific height.

$$M_{CFD} = M_{TH} = u^2 \rho \pi R^2$$

Rearranging both equations above leads to a definition of an equivalent top hat velocity u and radius R as follows:

$$u = \frac{M_{CFD}}{Q_{CFD} \cdot \rho}$$

$$R = Q_{CFD} \sqrt{\frac{\rho}{M_{CFD} \cdot \pi}}$$

M_{CFD}… Total momentum determined based on CFD results at a specific height (N)

Q_{CFD}… Total flow rate determined based on CFD results at a specific height (m^3/s)

M_{TH}… Total momentum of top hat profile (N)

Q_{TH}… Total flow rate of top hat profile (m^3/s)

u… Top hat velocity (m/s)

ρ… Top hat density (average plume density at a specific height determined based on CFD results) (kg/m^3)

R… Top hat radius (m)

Based on the correlations above, the equivalent top hat velocity and radius has been analysed at three different heights. The plume momentum and flow rate were determined by clipping the general up- and downdrafts ('clip-velocity') in the computational domain (caused by the general advection) and integrating the vertical velocities from the 'clip-velocity' (up to 0.47 m/s) to the peak plume rise velocity. This results in a slightly smaller plume flow rate (about 4% lower) and momentum (about 0.3% lower) compared to an integration from zero to the peak value. However, this was corrected by comparing the flow rate and momentum of a Gaussian velocity profile integrated from the 'clip-velocity' to the peak plume rise velocity, with the same profile integrated from zero to the peak plume rise velocity. The flow rate (Q_{CFD}) and momentum (M_{CFD}) are already the corrected values. Table 7 to Table 9 below lists the results of the correlation for all three analysed wind cases respectively. The plume for the 'combined' wind case has a transient behavior and has only been analysed for a specific simulation time (where peak plume rise velocity is close to their time-averaged value). The observed plume rise velocity fluctuations are about +/- 0.4 m/s (see Figure 23).

Table 7. Top hat profile equivalence for simulation with 'initial' wind case.

Plume definition	Unit	650 ft	700 ft	1000 ft
'Clip-velocity'*	m/s	0.47	0.47	0.47
Flow rate CFD (Q_{CFD})	m^3/s	59190.5	74078.5	161154.3
Momentum CFD (M_{CFD})	N	395793.7	442607.0	773700.0
Average density within the plume area (ρ)#	kg/m^3	1.217	1.221	1.223
Equivalent top hat velocity (u)	**m/s**	**5.5**	**4.9**	**3.9**
Equivalent top hat radius (R)	m	58.6	69.4	114.3
Max. plume rise velocity from CFD	**m/s**	**11.5**	**11.5**	**10.7**
Standard deviation**	m	28.0	29.6	42.0

*Integration is based on a minimum vertical velocity ('clip velocity') to avoid integration of general up- and downdrafts in the computational domain. 'Clip velocity' is the vertical velocity which defines the plume edge. General up- and downdrafts are below the 'Clip velocity' value.
#Average density within the plume area was determined based on the CFD results.
**Determined by adjusting a Gaussian velocity profile to the top hat profile by matching the momentum. Gaussian profile is based on the maximum plume rise velocity. This may not be meaningful for an oddly shaped plume.

Table 8. Top hat profile equivalence for simulation with calm wind case.

Plume definition	Unit	650 ft	700 ft	1000 ft
'Clip-velocity'*	m/s	0.40	0.29	0.29
Flow rate CFD (Q_{CFD})	m^3/s	86475.3	92791.7	144775.4
Momentum CFD (M_{CFD})	N	420974.6	452043.2	644547.1
Average density within the plume area (ρ)#	kg/m^3	1.186	1.187	1.190
Equivalent top hat velocity (u)	**m/s**	**4.1**	**4.1**	**3.7**
Equivalent top hat radius (R)	m	81.9	84.8	111.0
Max. plume rise velocity from CFD	**m/s**	**8.4**	**8.1**	**7.3**
Standard deviation**	m	40.0	42.9	56.3

*Integration is based on a minimum vertical velocity ('clip velocity') to avoid integration of general up- and downdrafts in the computational domain. 'Clip velocity' is the vertical velocity which defines the plume edge. General up- and downdrafts are below the 'Clip velocity' value.
#Average density within the plume area was determined based on the CFD results.
**Determined by adjusting a Gaussian velocity profile to the top hat profile by matching the momentum. Gaussian profile is based on the maximum plume rise velocity. This may not be meaningful for an oddly shaped plume.

Table 9. Top hat profile equivalence for simulation with 'combined' wind case at the analysed simulation time.

Plume definition	Unit	650 ft	700 ft	1000 ft
'Clip-velocity'*	m/s	0.29	0.35	0.40
Flow rate CFD (Q_{CFD})	m^3/s	45582.0	50508.5	81808.8
Momentum CFD (M_{CFD})	N	366833.9	402915.9	607395.9
Average density within the plume area (ρ)#	kg/m^3	1.206	1.206	1.213
Equivalent top hat velocity (u)	**m/s**	**6.7**	**6.6**	**6.1**
Equivalent top hat radius (R)	m	46.6	49.3	65.2
Max. plume rise velocity from CFD	**m/s**	**11.9**	**11.7**	**10.5**
Standard deviation**	m	25.8	27.4	37.9

*Integration is based on a minimum vertical velocity ('clip velocity') to avoid integration of general up- and downdrafts in the computational domain. 'Clip velocity' is the vertical velocity which defines the plume edge. General up- and downdrafts are below the 'Clip velocity' value.
#Average density within the plume area was determined based on the CFD results.
**Determined by adjusting a Gaussian velocity profile to the top hat profile by matching the momentum. Gaussian profile is based on the maximum plume rise velocity. This may not be meaningful for an oddly shaped plume.

Beyond the discussion of the relevant average plume rise velocity and the top hat profile equivalence approach in section 4, CASA stated in their letter [12] that they will accept half of the peak plume rise velocity as measure for potential impacts on aircraft.

5 REFERENCES

[1] Ansys, Inc.: ANSYS Fluent User's Guide, Release 2019 R3, USA, August 2019

[2] Ansys, Inc.: ANSYS Fluent Theory Guide, Release 2019 R3, USA, August 2019

[3] Ansys, Inc.: ANSYS Fluid Dynamics Verification Manual, Release 2019 R3, USA, August 2019

[4] Launder, B. E. & Spalding, D. B. (1972). Lectures in Mathematical Models of Turbulence. London, UK: Academic Press.

[5] Launder, B. E. & Spalding, D. B. (1974). The Numerical Computation of Turbulent Flows. Computer Methods in Applied Mechanics and Engineering, 3, S. 269-289.

[6] Meteorological data (case: 20140703_10) provided to Stacey Agnew on 31 January 2020 per email.

[7] Meteorological data (case: 20150308) provided to Stacey Agnew on 28 April 2021 per email.

[8] GE Exhaust Stack Modification for CASA Compliance 02April2020.pdf provided to Stacey Agnew on 15 April 2020 per email.

[9] Terrain data provided to Stacey Agnew on 5 February 2020 per email.

[10] Stacey Agnew: Tallawarra B Power Station CFD Plume Modelling – Validation Case, Short Summary Report from 11th February 2020 - Draft.

[11] Ambient temperature variation and resulting stack outlet conditions provided to Stacey Agnew on 15 June 2020 per email.

[12] Australian Government – Civil Aviation Safety Authority – Air Navigation, Airspace and Aerodromes, Letter regarding Tallawarra B Gas-Fire Power Station Project, File Ref: F17/8039-27 from 29/03/2021.

APPENDIX A

A.1. Calm Wind Case (Wind and Temperature Profile: 20150308 – Calm)

Figure 25 (left) shows the maximum vertical and absolute plume velocity against height as well as the atmospheric wind speed profile according to Figure 1. The maximum plume velocity reaches the ambient wind value at approximately 700 m (2297 ft) above the ground level. The maximum vertical plume velocity at this point is about 2.3 m/s. The plume temperature (right side of Figure 25) decreases rapidly with height and comes to within 0.5°C of the ambient value at about 700 m (2297 ft) above ground.

Figure 26 depicts the plume area against height (left) and the average plume velocities (right) within this area. Here the plume area is defined as horizontal area in which the vertical plume velocity is > 6 m/s. In addition, Figure 27 shows a similar plot and compares the plume area and average vertical plume velocity for different plume area definitions (area in which vertical plume velocity is > 6 m/s, > 4 m/s, > 2 m/s and > 1 m/s).

Figure 28 illustrates the velocity and temperature distribution of the initial jet flow region and Figure 29 the plume extent for the different vertical plume velocity criteria, based on value-clipped contour plots for vertical velocity.

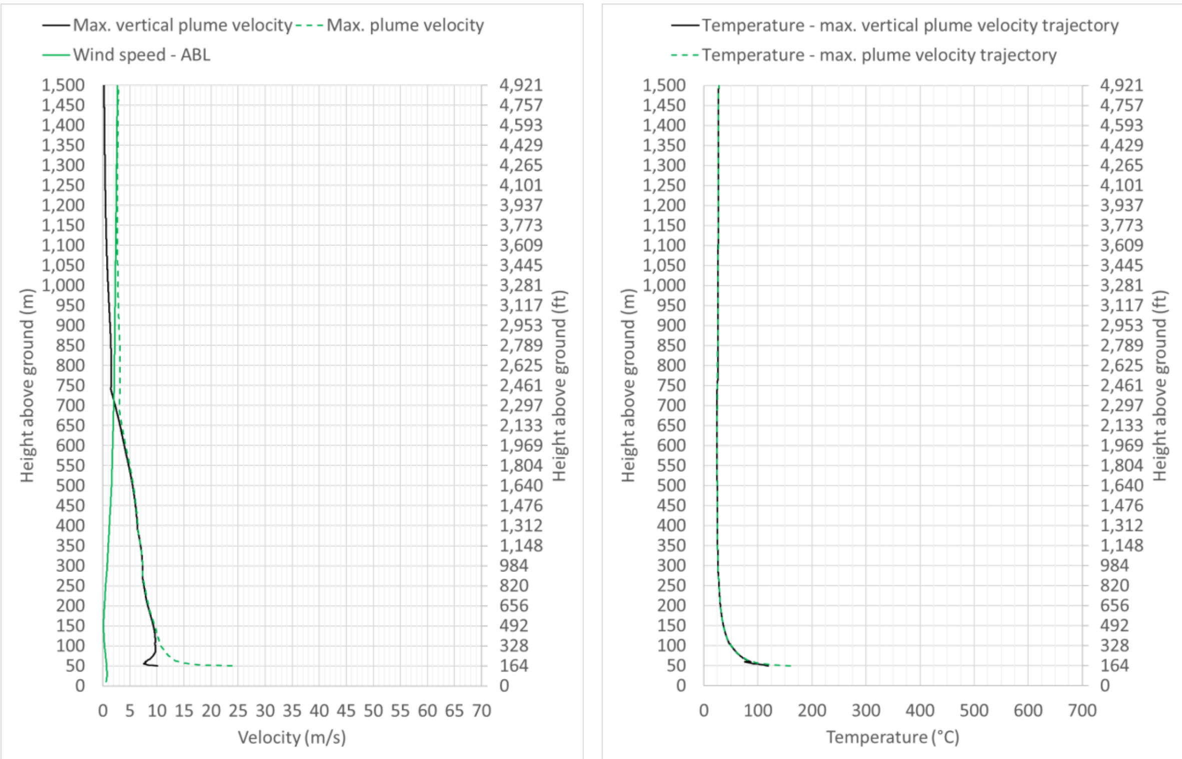


Figure 25. Wind speed and maximum vertical and absolute plume velocity against height (left) and plume temperature along both trajectories (right) – Calm wind case.

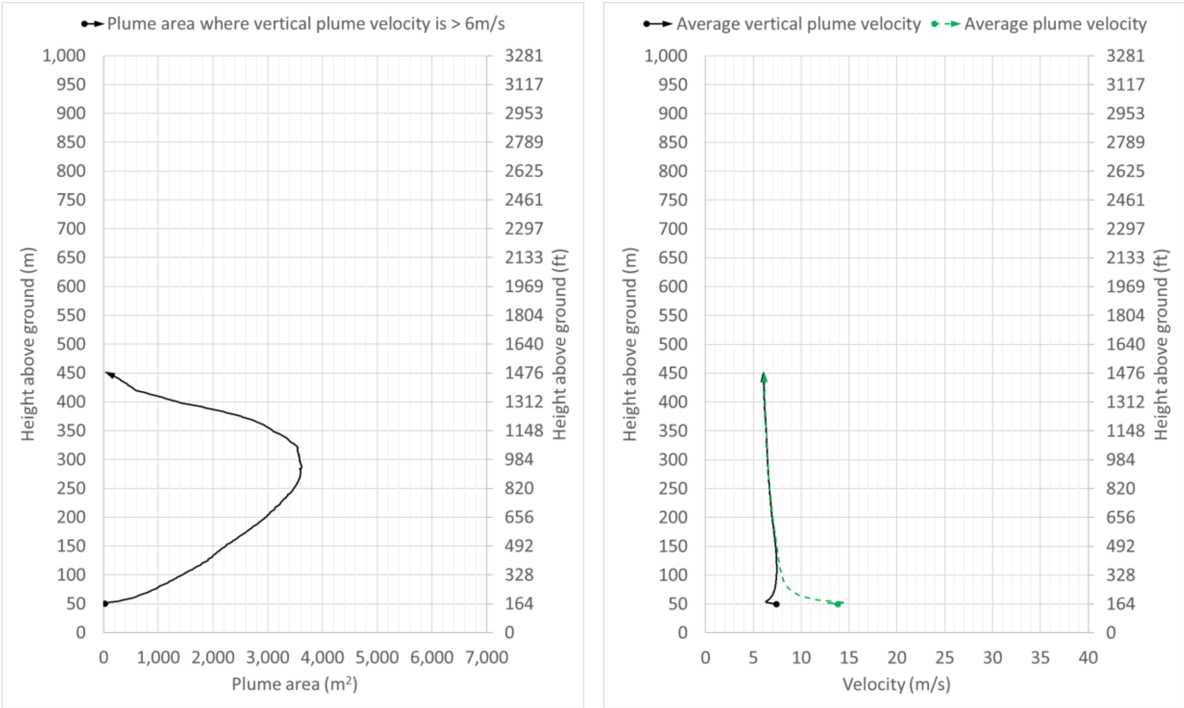


Figure 26. Plume area (area where vertical plume velocity is > 6 m/s) (left) and average plume velocities against height (right) – Calm wind case. Note that with the definition of plume area as being where the vertical velocity exceeds 6 m/s, the average vertical velocity in the 'plume' clearly can't fall below 6 m/s.

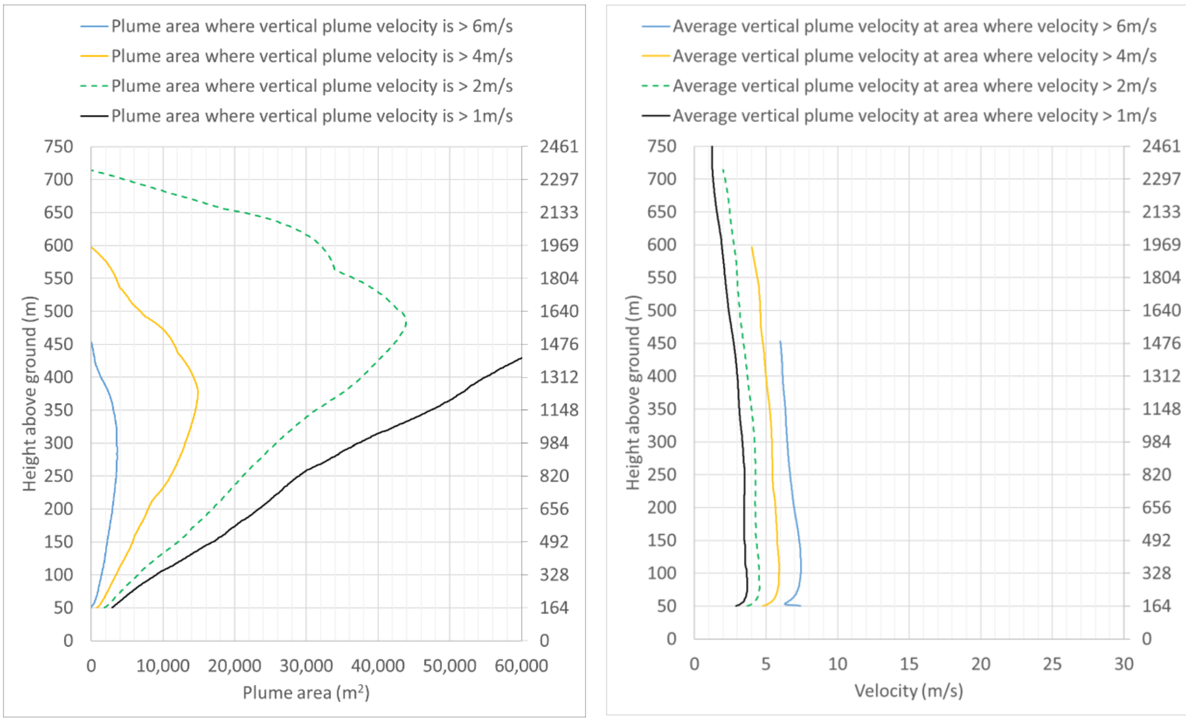
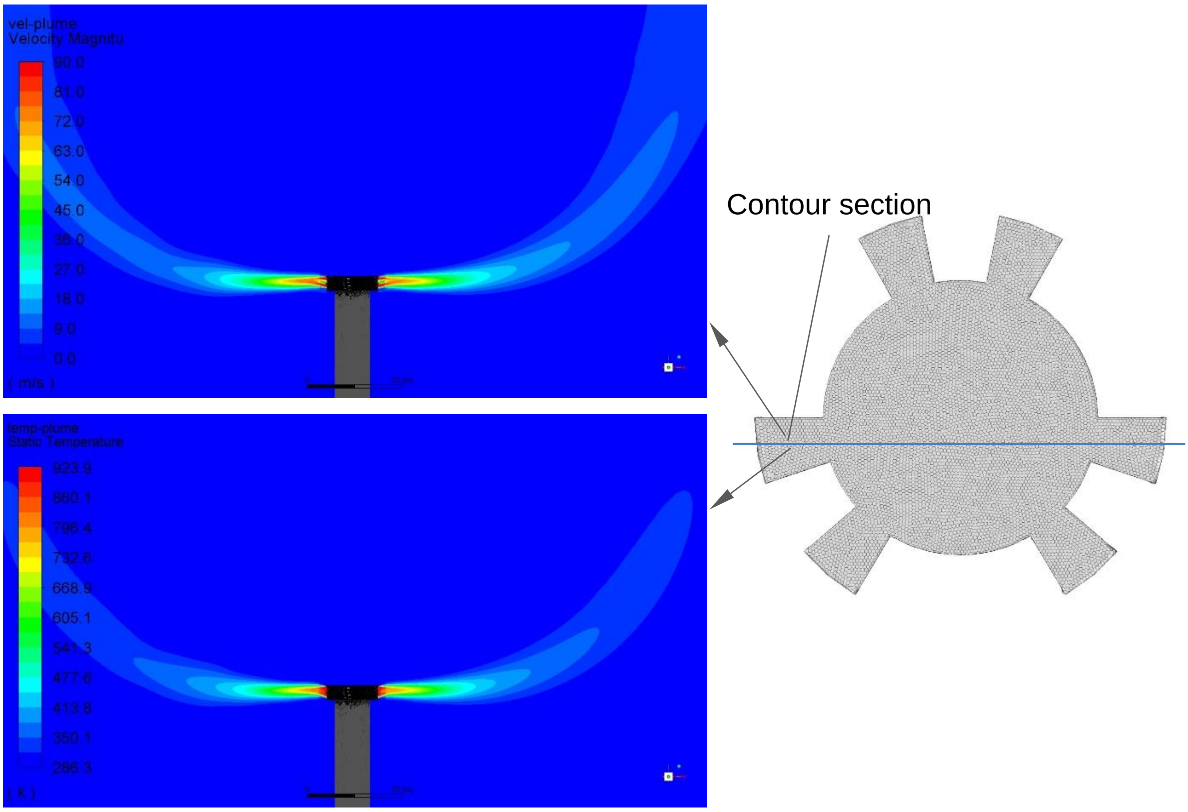
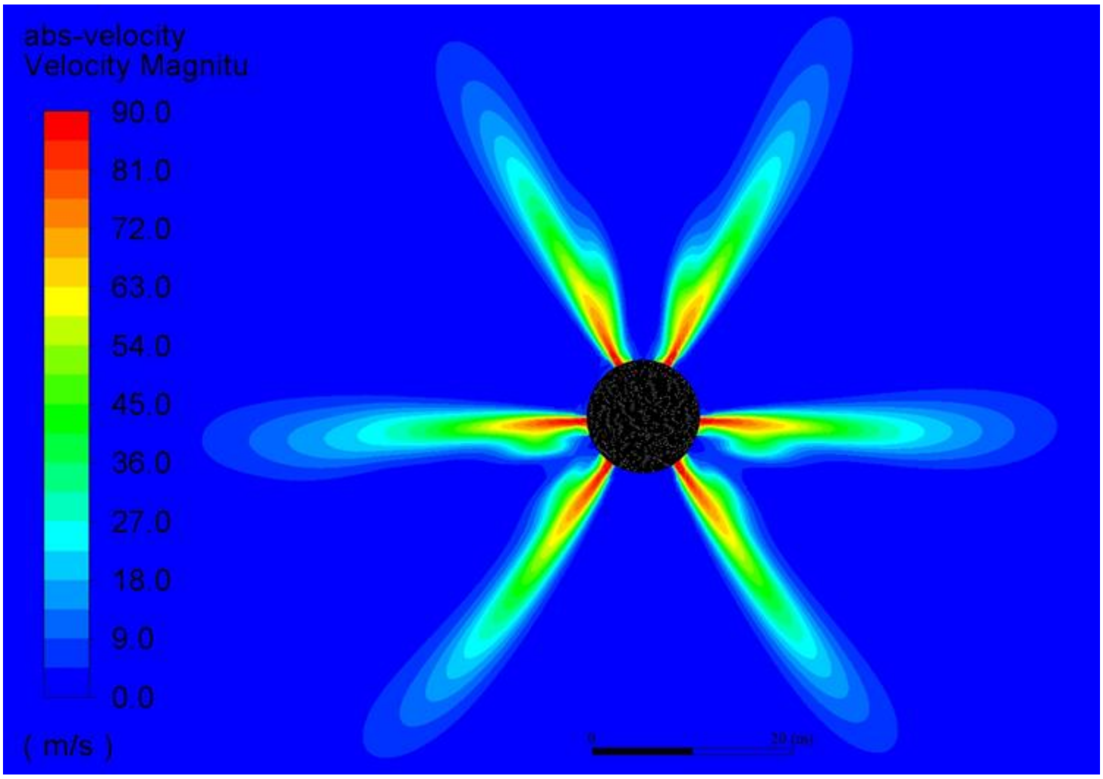


Figure 27. Plume area (left) and average plume velocities against height (right) for different plume area definitions - Calm wind case.


vel-plume
Velocity Magnitu
90.0
81.0
72.0
63.0
54.0
45.0
36.0
27.0
18.0
9.0
0.0
(m/s)
temp-plume
Static Temperature
923.9
860.1
796.4
732.6
668.9
605.1
541.3
477.6
413.8
350.1
286.3
(K)
Contour section


abs-velocity
Velocity Magnitu
90.0
81.0
72.0
63.0
54.0
45.0
36.0
27.0
18.0
9.0
0.0
(m/s)

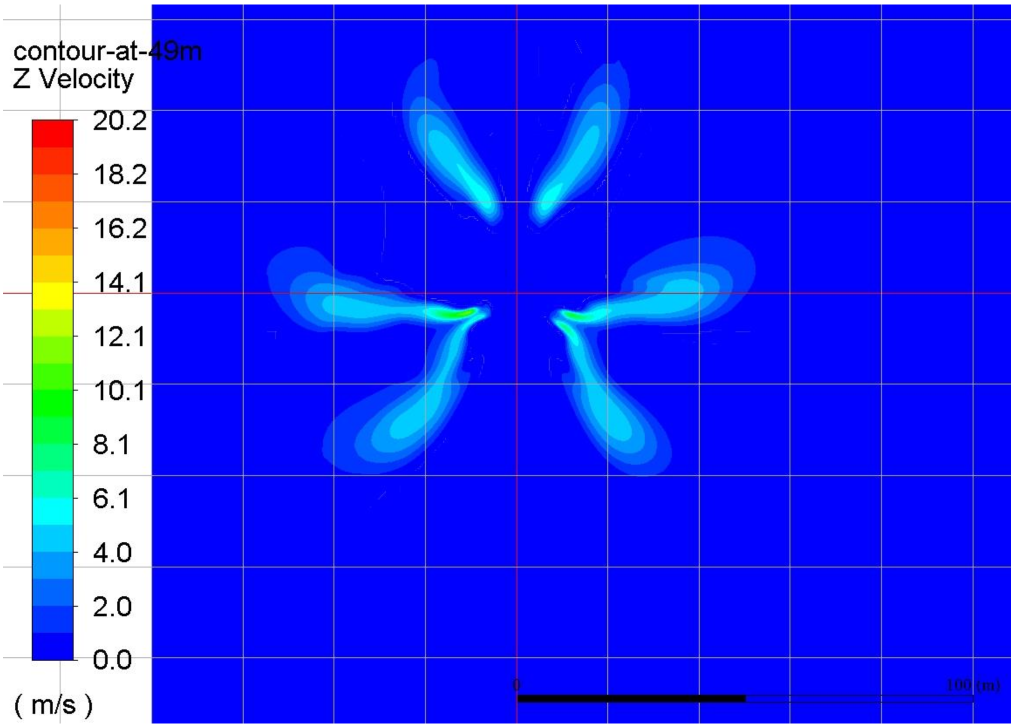


Figure 28. Contour of velocity (top picture) and temperature (2nd picture from the top) close to the stack outlet, as well as contour of velocity through the upper nozzle openings (3rd picture from the top) and about 2 m above the stack outlet in plane view (bottom, grid spacing is 20 m with stack centre at the origin.) - Calm wind case.

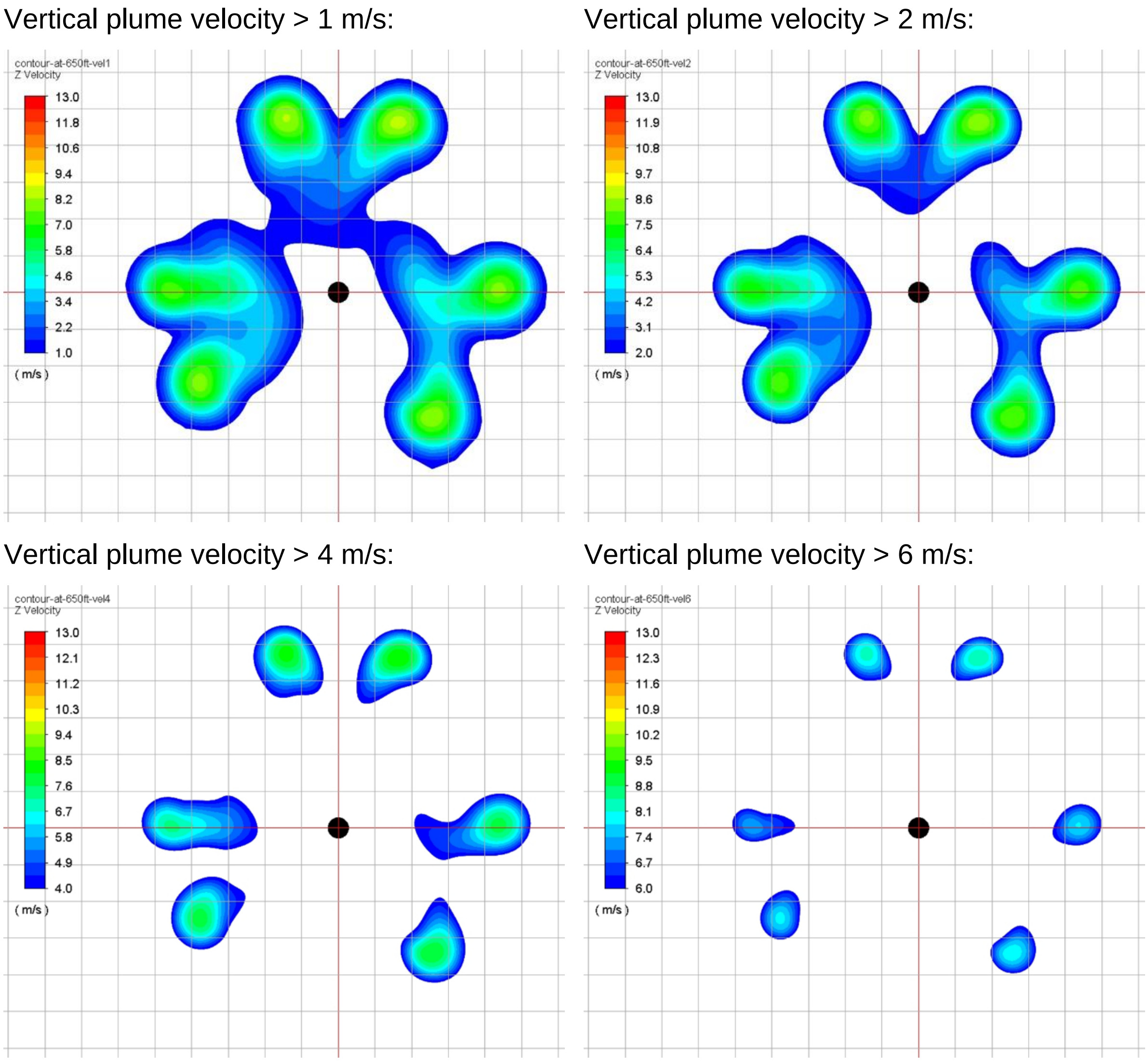


Figure 29. Plume extent shown as a contour plots of vertical velocity in a horizontal plane at 198 m (650 ft) elevation – Calm wind case. The plume area in each contour plot is clipped to a different vertical plume velocity: > 6 m/s (bottom right), > 4 m/s (bottom left), > 2 m/s (top right) and > 1 m/s (top left). Grid spacing is 20 m with stack centre at the origin (red lines).

Figure 30 depicts the growth in horizontal displacement of the locations of the maximum absolute plume velocity and maximum vertical velocity. The coordinates are based on the domain, which means that positive y aligns with the direction ESE (107°) and positive x with SSW (197°). The total horizontal displacement of the plume core is approximately 170 m.

Figure 31 shows the horizontal trajectory of the maximum vertical velocity component as well as the maximum absolute plume velocity in compass coordinates (abscissa towards North and ordinate towards East).

Both Figure 30 and Figure 31 show discontinuities that are associated with minor oscillations in the individual jets interacting with the ambient wind, such that the location of the maximum vertical velocity jumps around between the individual jets, creating a pattern that is hard to interpret.

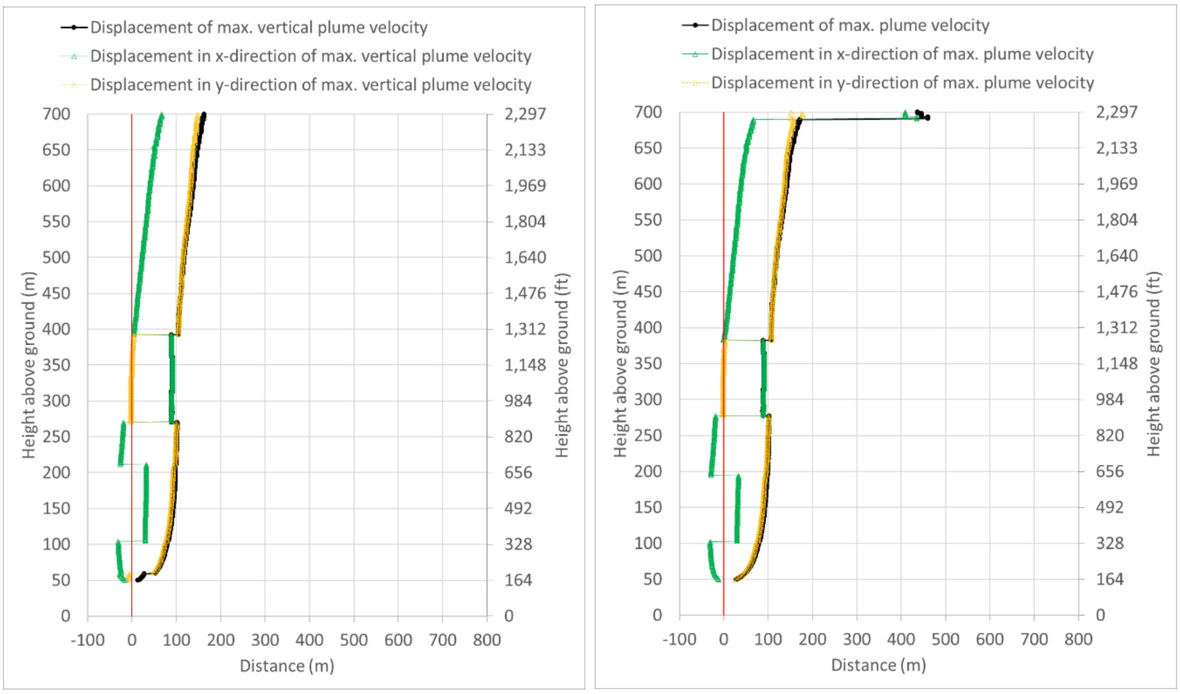


Figure 30. Displacement of maximum vertical velocity component (left) and of absolute core velocity (right) against height – Calm wind case.

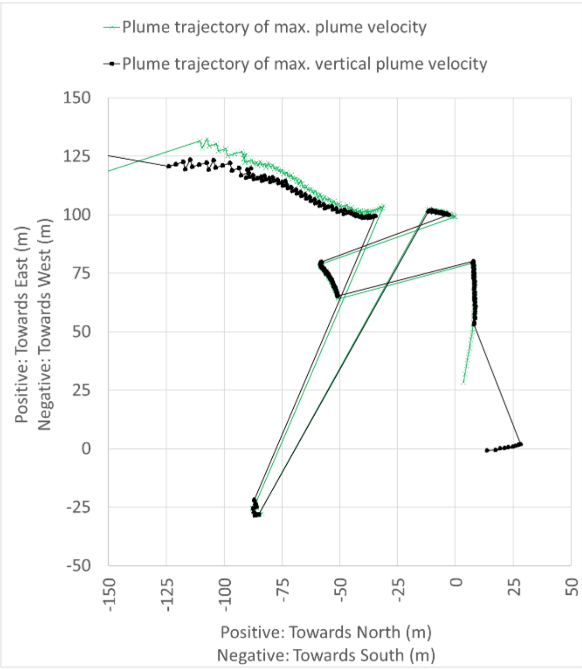


Figure 31. Horizontal trajectory of maximum vertical velocity and plume core velocity in compass coordinates – Calm wind case.

Figure 32 to Figure 36 are contour plots of velocity magnitude, vertical velocity, and air temperature on x-z and y-z planes through the stack centre, or on horizontal planes at different heights. The black lines in Figure 34 to Figure 36 show the x and y planes through the stack centre. Contours are clipped for clarity.

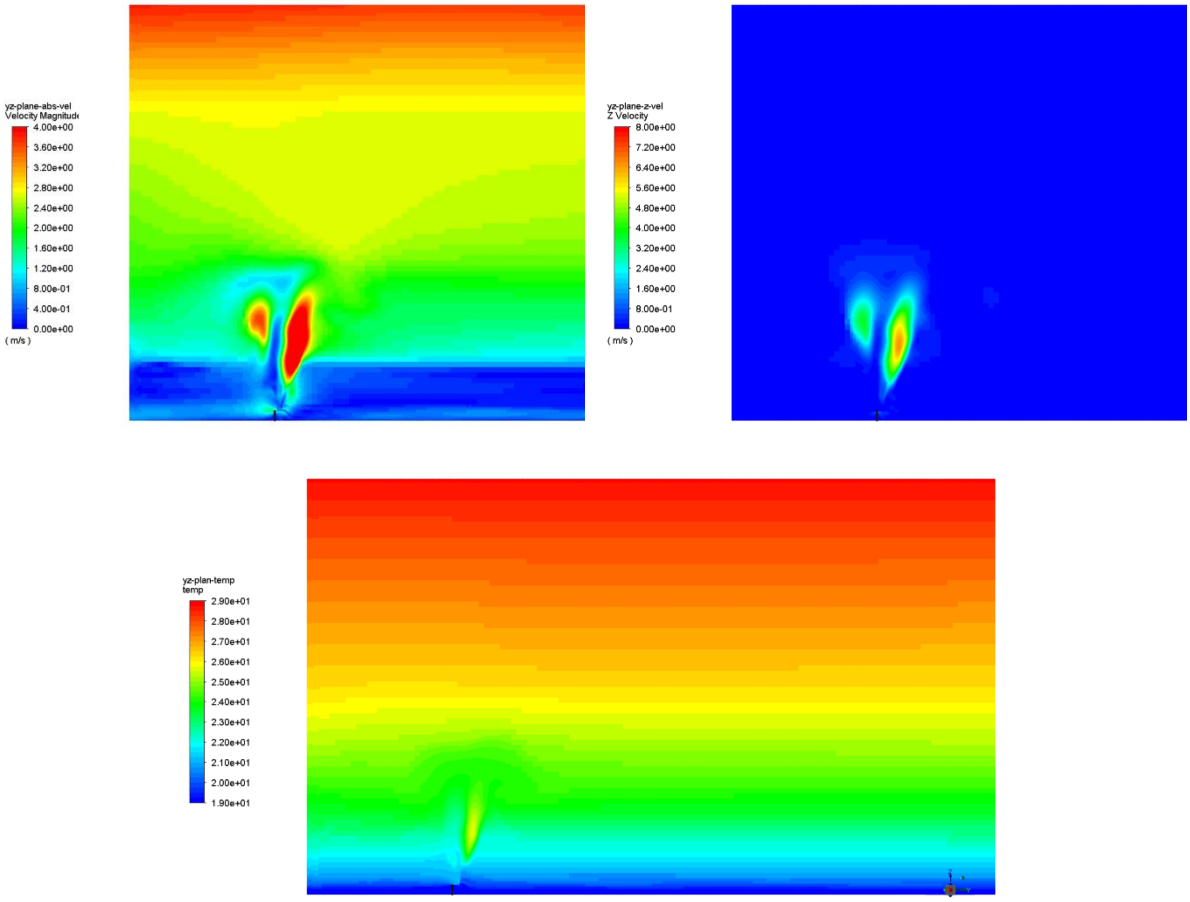


Figure 32. Contour plot in y-z plane through the stack centre for velocity magnitude (upper left), vertical velocity (upper right), and temperature (bottom) – Calm wind case.

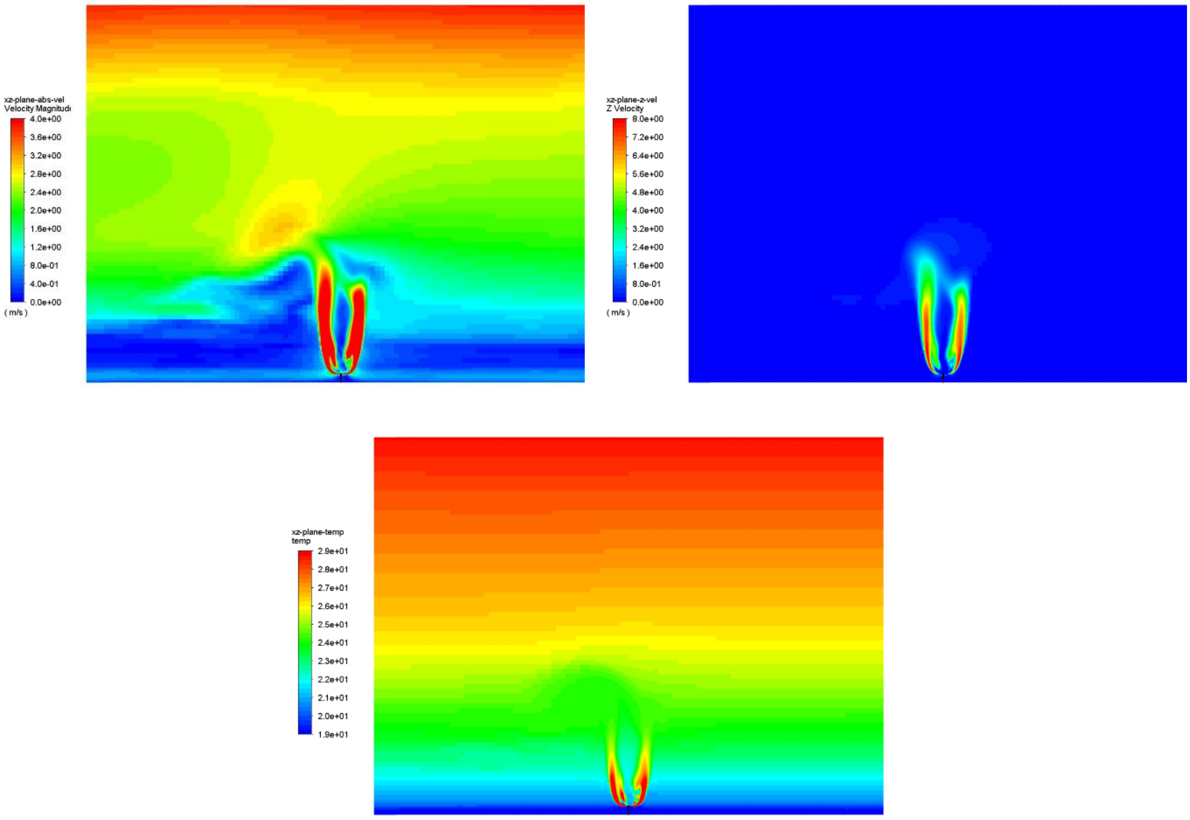


Figure 33. Contour plot in x-z plane through the stack centre for velocity magnitude (upper left), vertical velocity (upper right), and temperature (bottom) – Calm wind case.

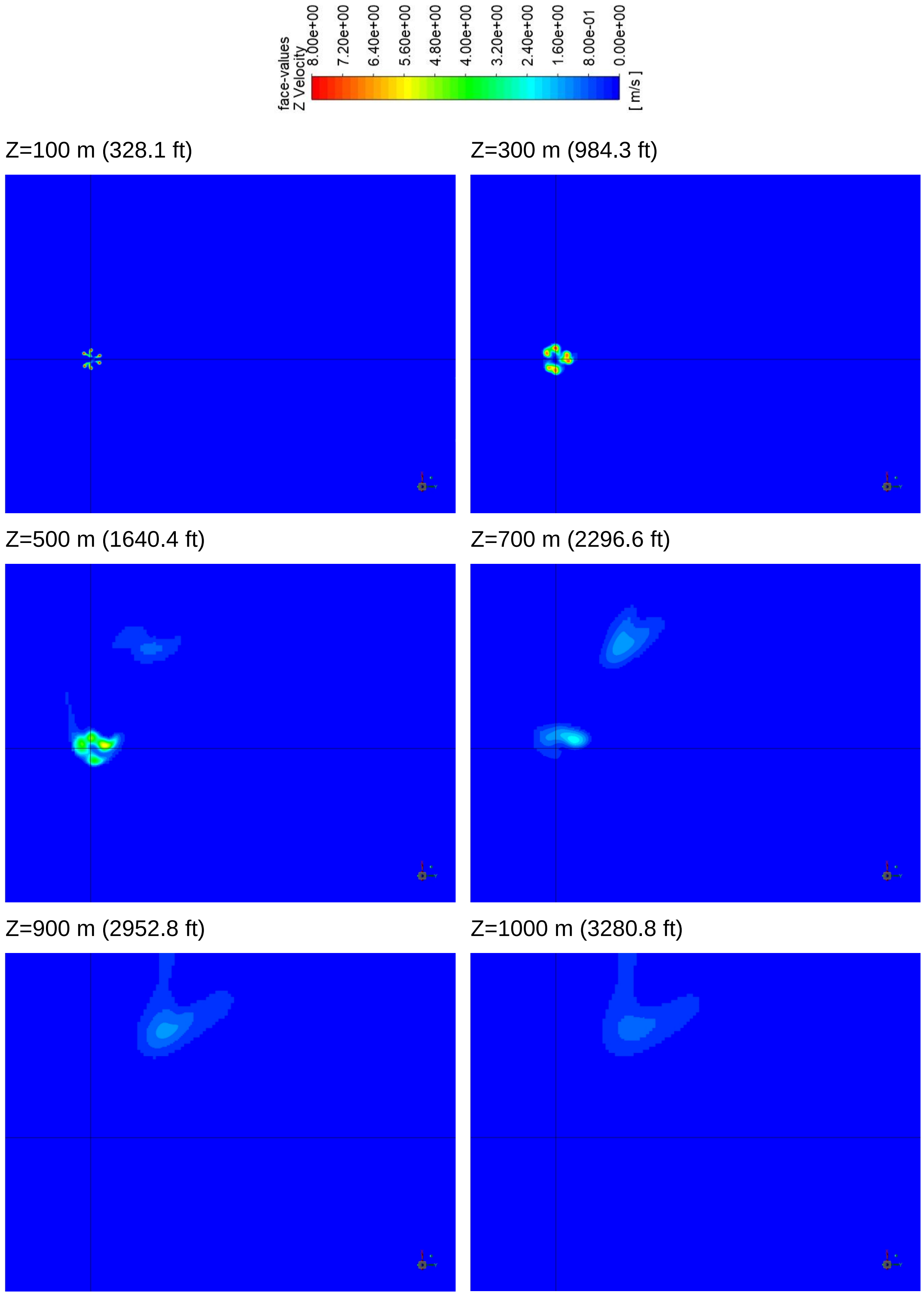


Figure 34. Contour plot of vertical velocity in plan at different horizontal plane heights – Calm wind case. Black lines define the stack centre.

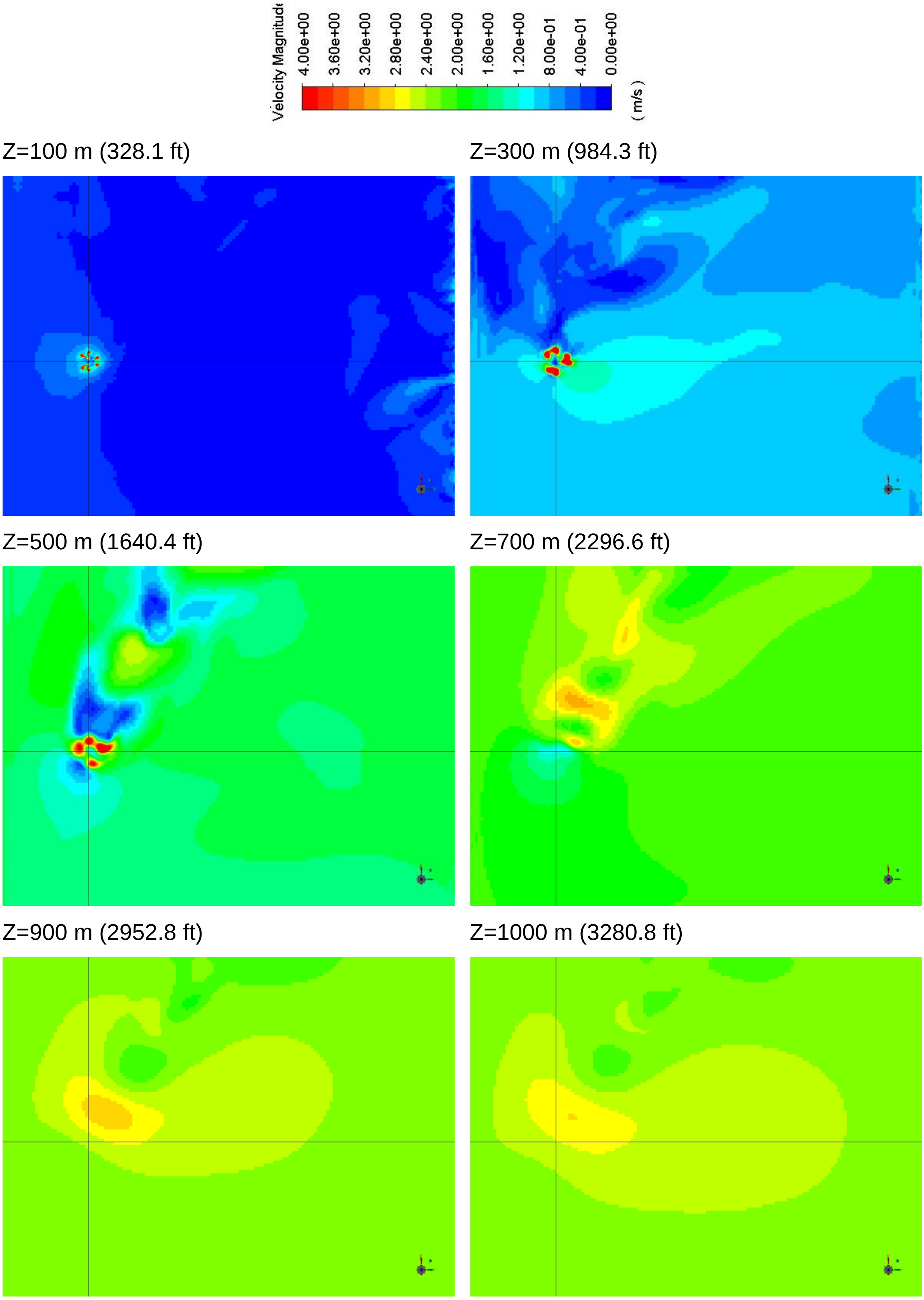


Figure 35. Contour plot of velocity magnitude in plan at different horizontal plane heights - Calm wind case. Black lines define the stack centre.

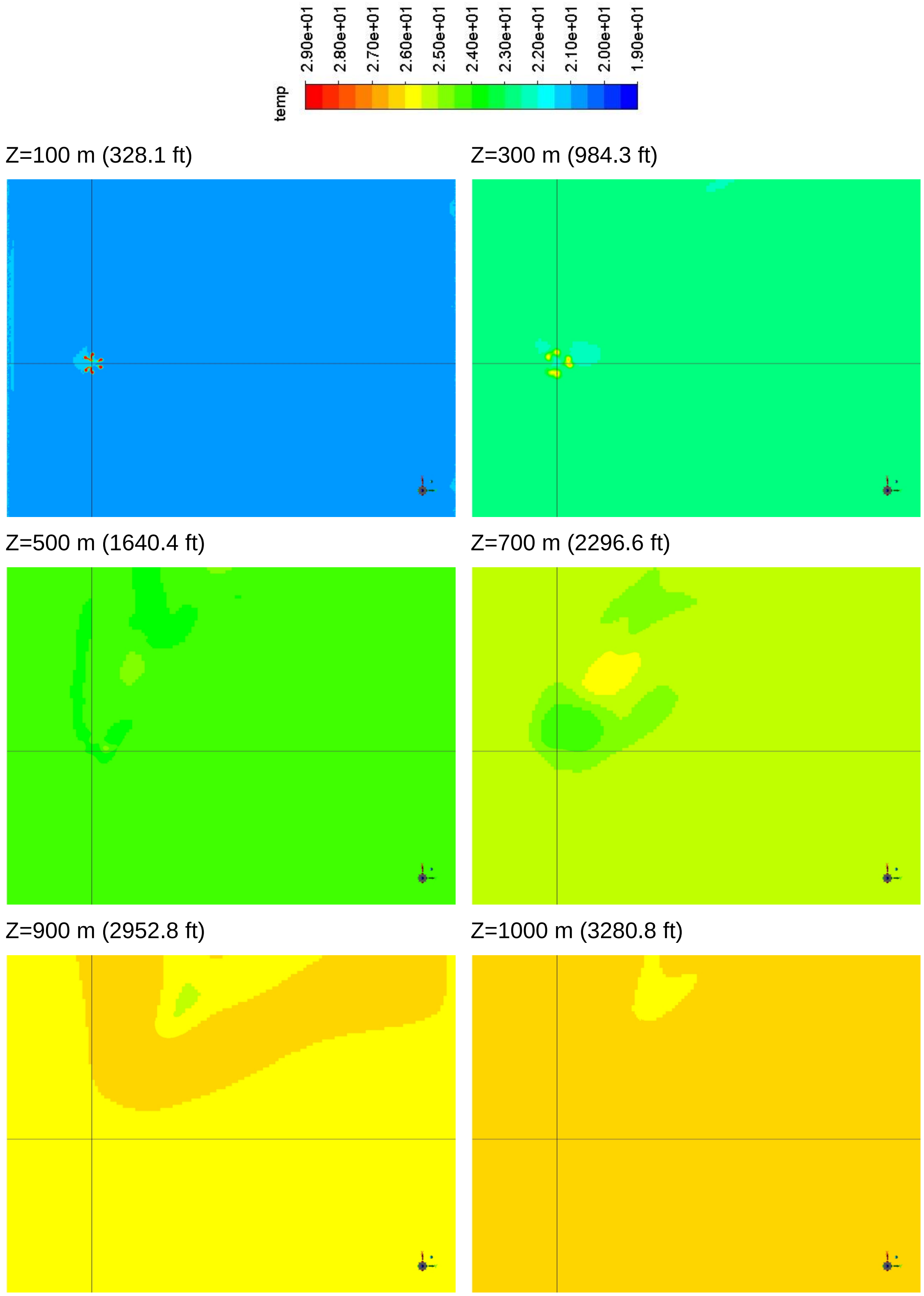


Figure 36. Contour plots of temperature in plan at different heights - Calm wind case. Black lines define the stack centre.

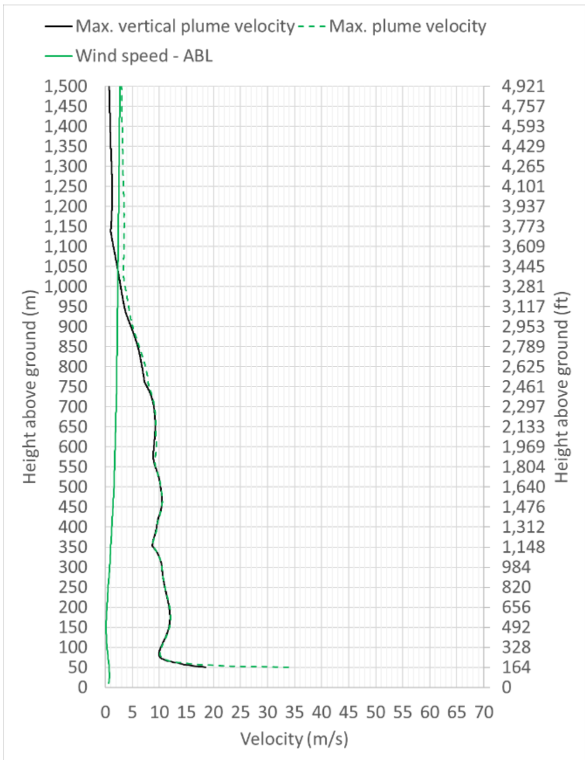
A.2. 'Combined' Wind Case (Wind profile: 20150308 – Calm and Temperature profile 20140703_10)

As discussed in Section 3.4, the plume behavior for this wind case is transient. All the plots and figures were analysed at a specific point in time where the peak plume rise velocity was close to their time-averaged value (see Figure 23).

Figure 37 (left) shows the maximum vertical and absolute plume velocity against height as well as the atmospheric wind speed profile according to Figure 1. The maximum plume velocity reaches the ambient wind value at approximately 1050 m (3445 ft) above the ground level. The maximum vertical plume velocity at this point is about 2.2 m/s. The plume temperature (right side of Figure 37) decreases rapidly with height and comes to within 0.5°C of the ambient value at about 870 m (2854 ft) above ground.

Figure 38 depicts the plume area against height (left) and the average plume velocities (right) within this area. Here the plume area is defined as horizontal area in which the vertical plume velocity is > 6 m/s. In addition, Figure 39 shows a similar plot and compares the plume area and average vertical plume velocity for different plume area definitions (area in which vertical plume velocity is > 6 m/s, > 4 m/s, > 2 m/s and > 1 m/s).

Figure 40 illustrates the velocity and temperature distribution of the initial jet flow region and Figure 41 the plume extent for the different vertical plume velocity criteria, based on value-clipped contour plots for vertical velocity.



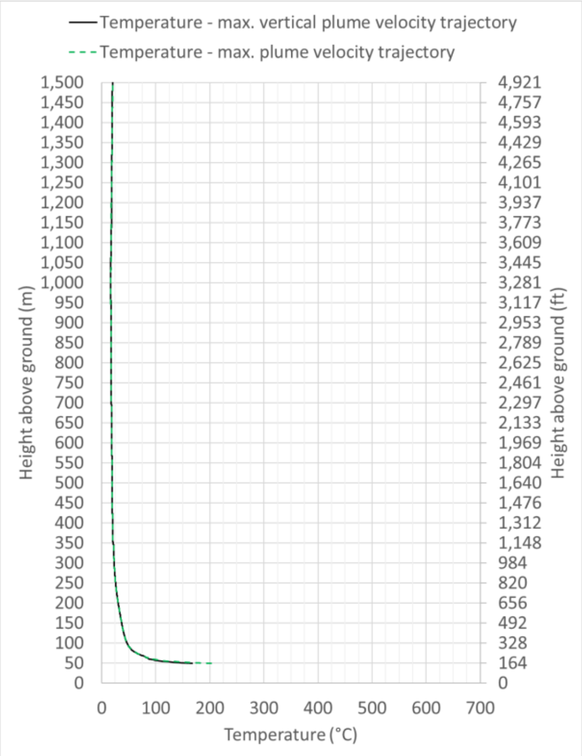


Figure 37. Wind speed and maximum vertical and absolute plume velocity against height (left) and plume temperature alonge both trajectories (right) – 'Combined' wind case at analysed simulation time.

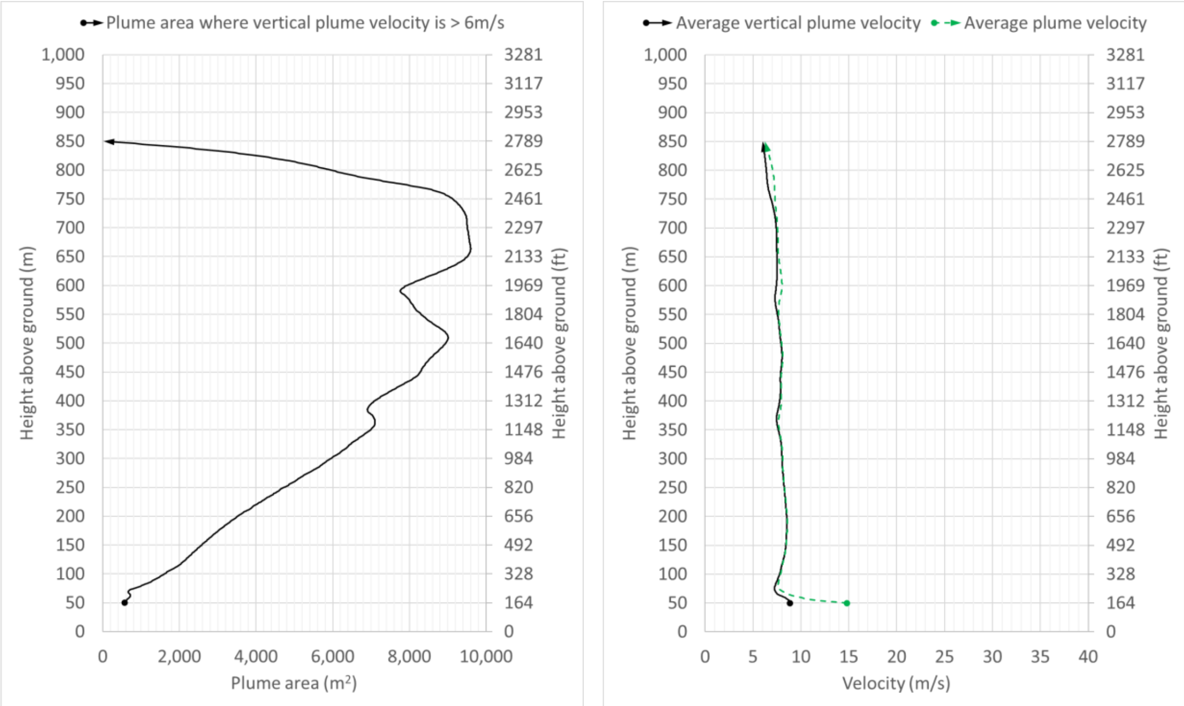


Figure 38. Plume area (area where vertical plume velocity is > 6 m/s) (left) and average plume velocities against height (right) - 'Combined' wind case at analysed simulation time. Note that with the definition of plume area as being where the vertical velocity exceeds 6 m/s, the average vertical velocity in the 'plume' clearly can't fall below 6 m/s.

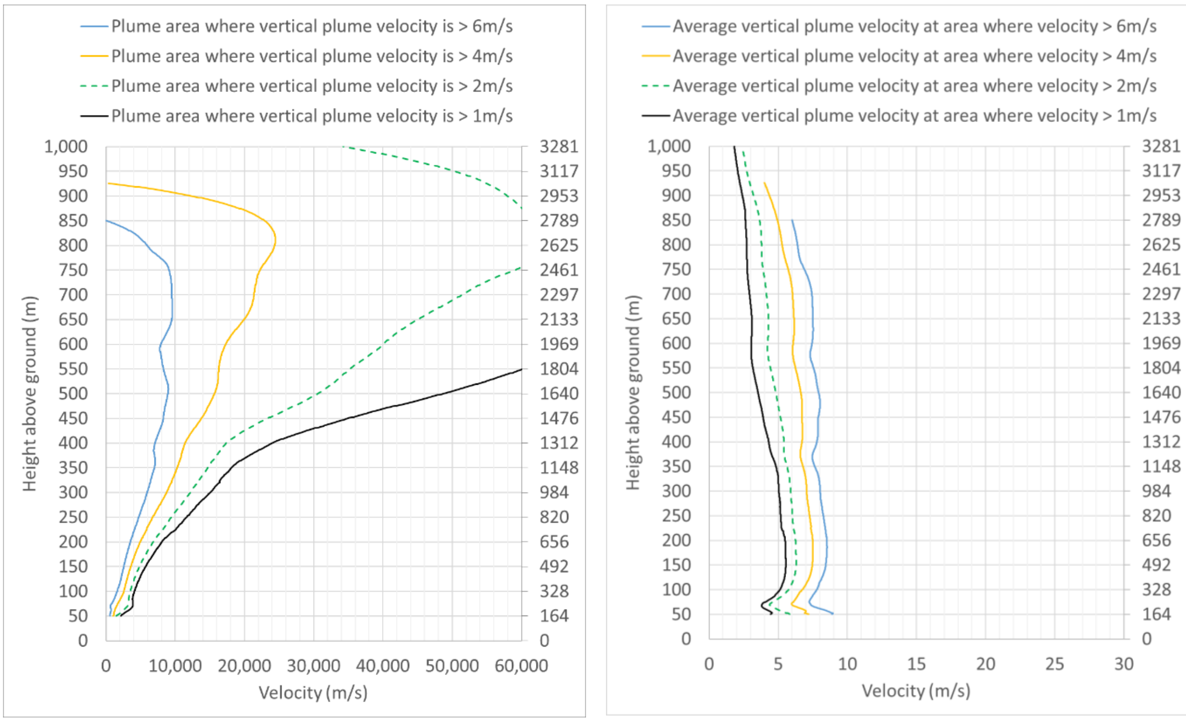


Figure 39. Plume area (left) and average plume velocities against height (right) for different plume area definitions - 'Combined' wind case at analysed simulation time.

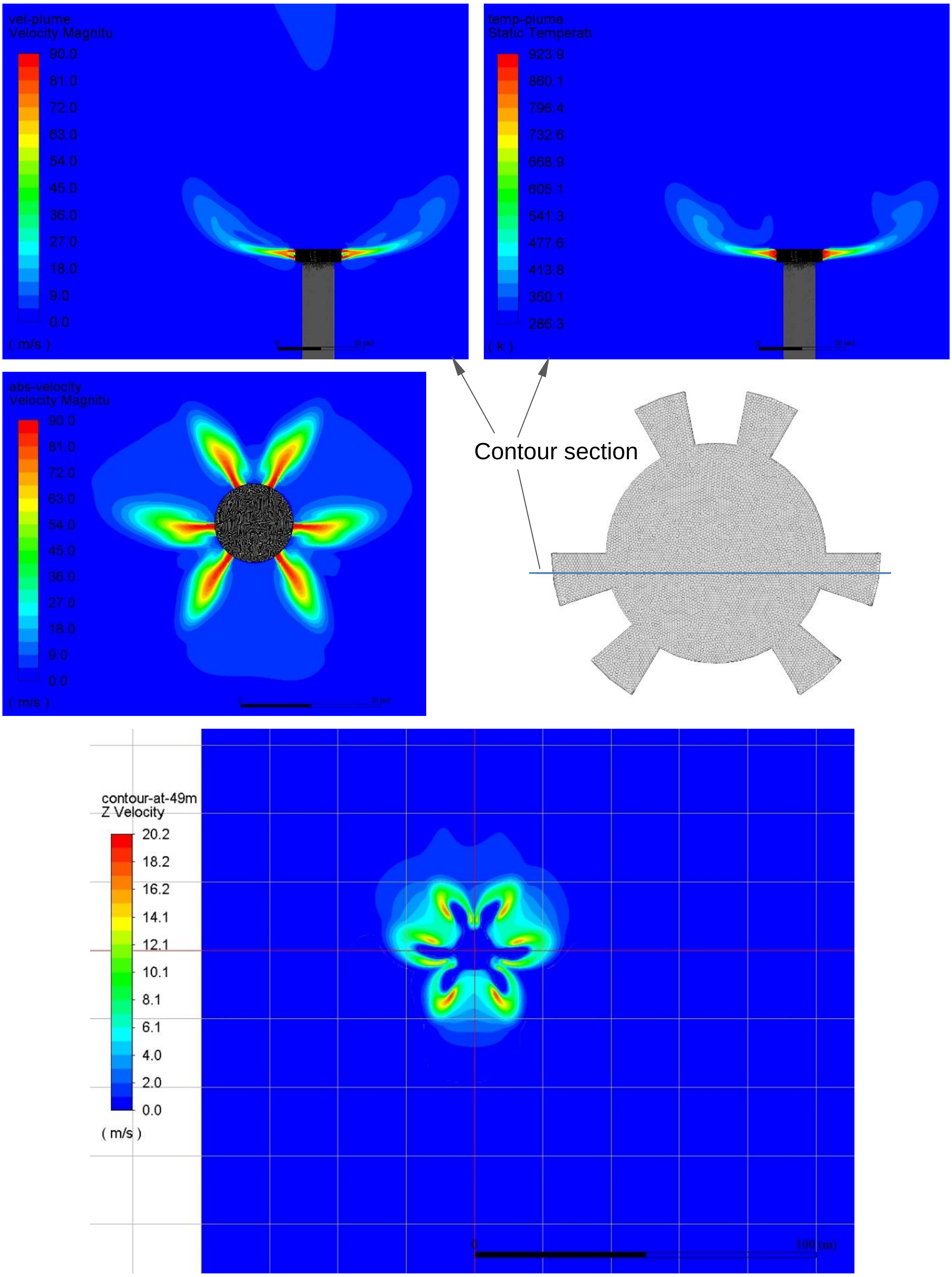
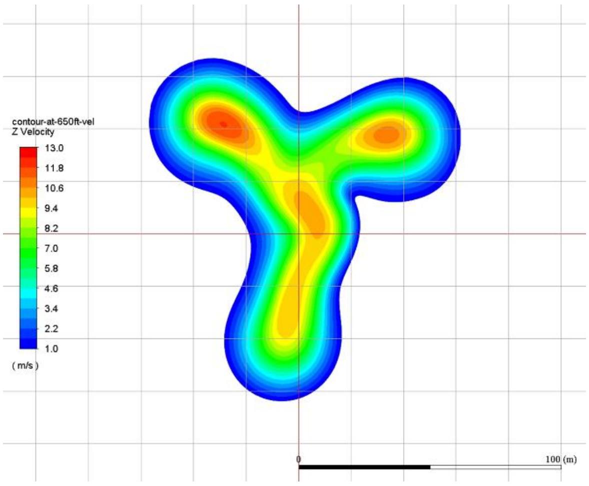
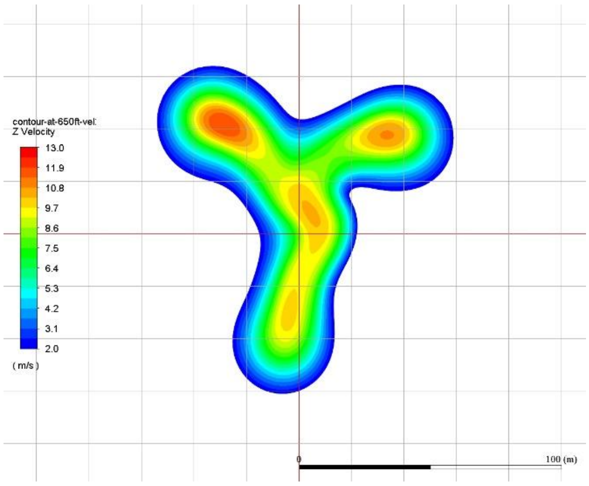


Figure 40. Contour of velocity (top left) and temperature (top right) close to the stack outlet as well as contour of velocity through the upper nozzle openings (middel) and about 2 m above the stack outlet in plane view (bottom) - 'Combined' wind case at analysed simulation time. Grid spacing in bottom picture is 20 m with stack centre at the origin.

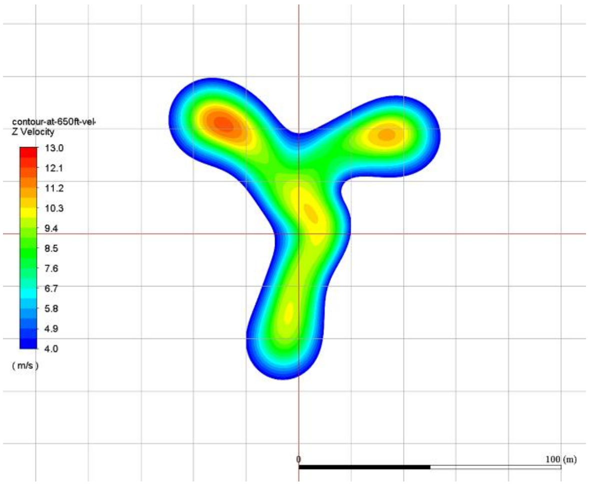
Vertical plume velocity > 1 m/s:



Vertical plume velocity > 2 m/s:



Vertical plume velocity > 4 m/s:



Vertical plume velocity > 6 m/s:

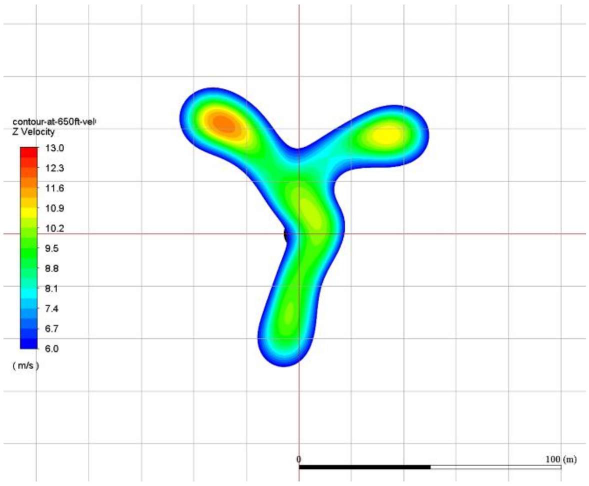


Figure 41. Plume extent shown as a contour plots of vertical velocity in a horizontal plane at 198 m (650 ft) elevation - 'Combined' wind case at analysed simulation time. The plume area in each contour plot is clipped to a different vertical plume velocity: > 6 m/s (bottom right), > 4 m/s (bottom left), > 2 m/s (top right) and > 1 m/s (top left). Grid spacing is 20 m with stack centre at the origin (red lines).

Figure 42 depicts the growth in horizontal displacement of the locations of the maximum absolute plume velocity and maximum vertical velocity. The coordinates are based on the domain, which means that positive y aligns with the direction ESE (107°) and positive x with SSW (197°). The total horizontal displacement of the plume core is approximately 220 m.

Figure 43 shows the horizontal trajectory of the maximum vertical velocity component as well as the maximum absolute plume velocity in compass coordinates (abscissa towards North and ordinate towards East).

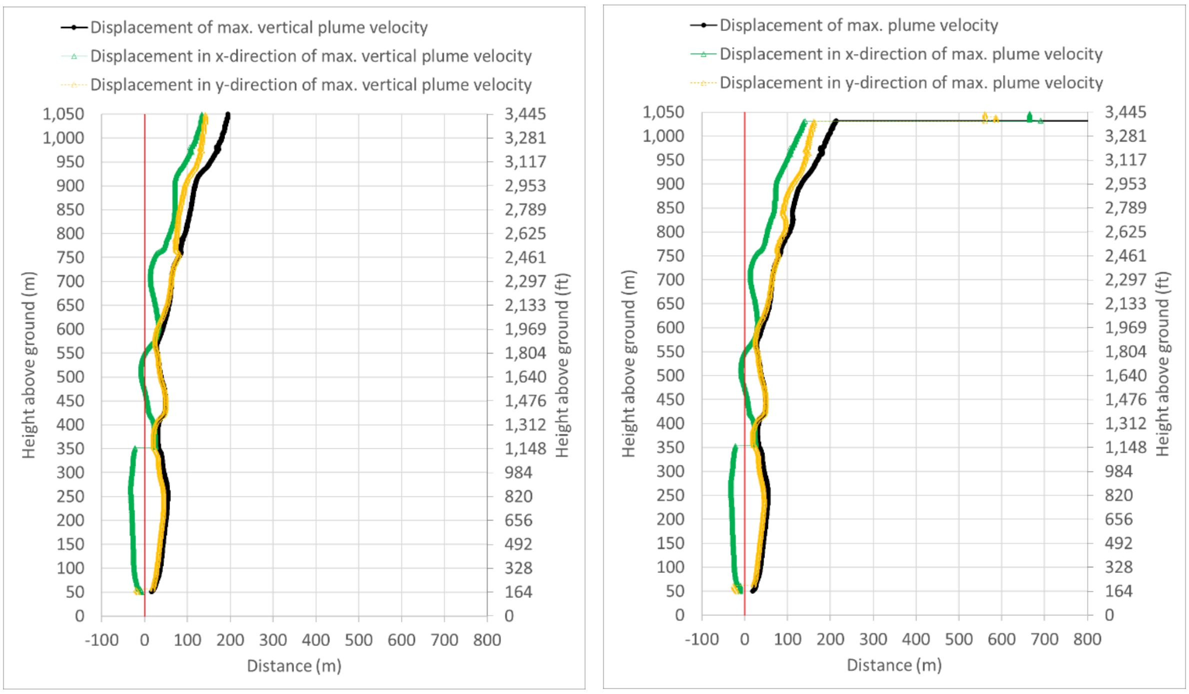


Figure 42. Displacement of maximum vertical velocity component (left) and of absolute core velocity (right) against height - 'Combined' wind case at analysed simulation time.

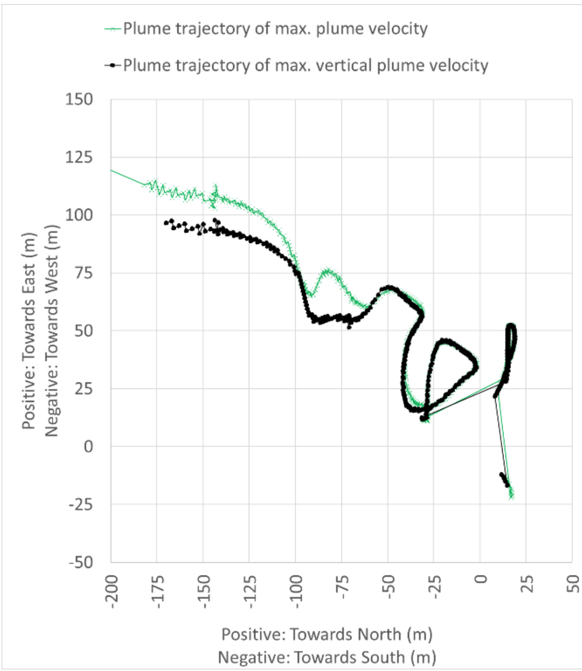


Figure 43. Horizontal trajectory of maximum vertical velocity and plume core velocity in compass coordinates - 'Combined' wind case at analysed simulation time.

Figure 44 to Figure 48 depict contour plots of velocity magnitude, vertical velocity, and air temperature on x-z and y-z planes through the stack centre, or on horizontal planes at different heights. The black lines in Figure 46 to Figure 48 show the x and y planes through the stack centre. Contours are clipped for clarity.

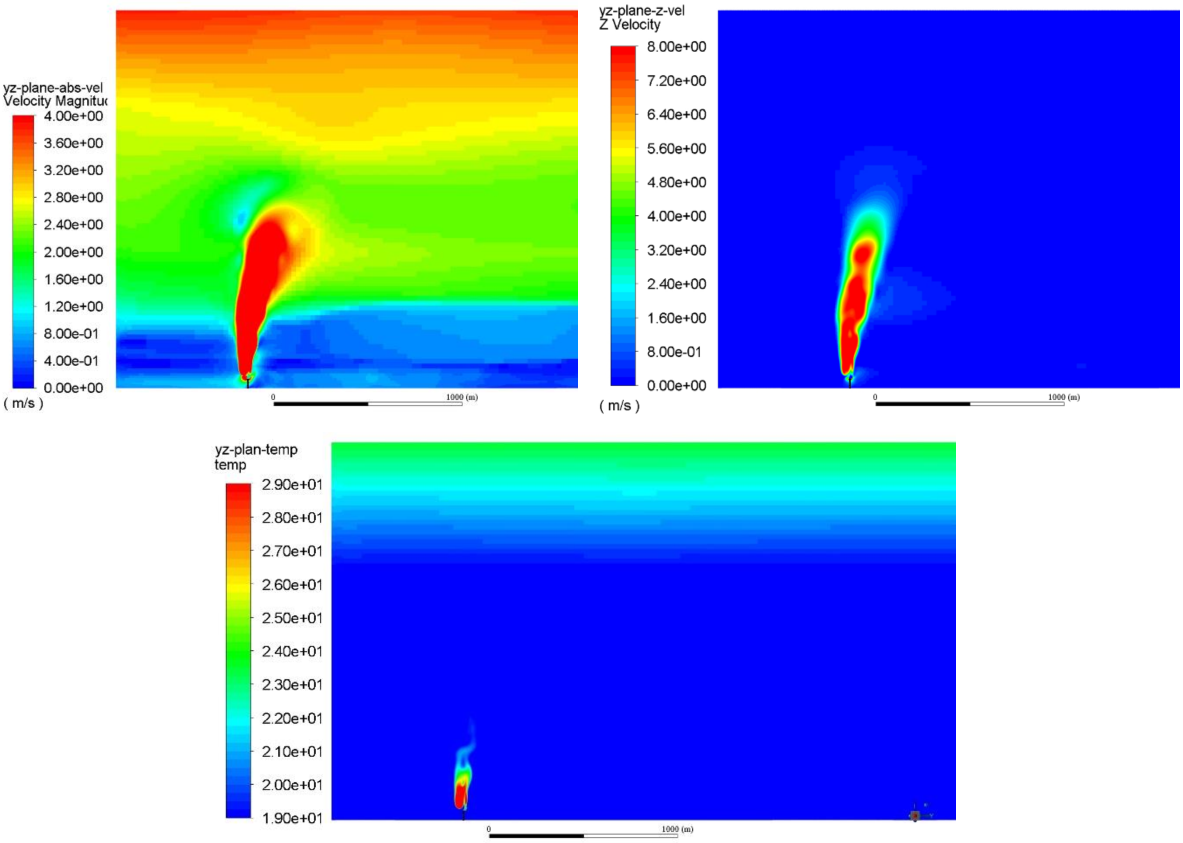


Figure 44. Contour plot in y-z plane through the stack centre for velocity magnitude (upper left), vertical velocity (upper right), and temperature (bottom) – 'Combined' wind case at analysed simulation time.

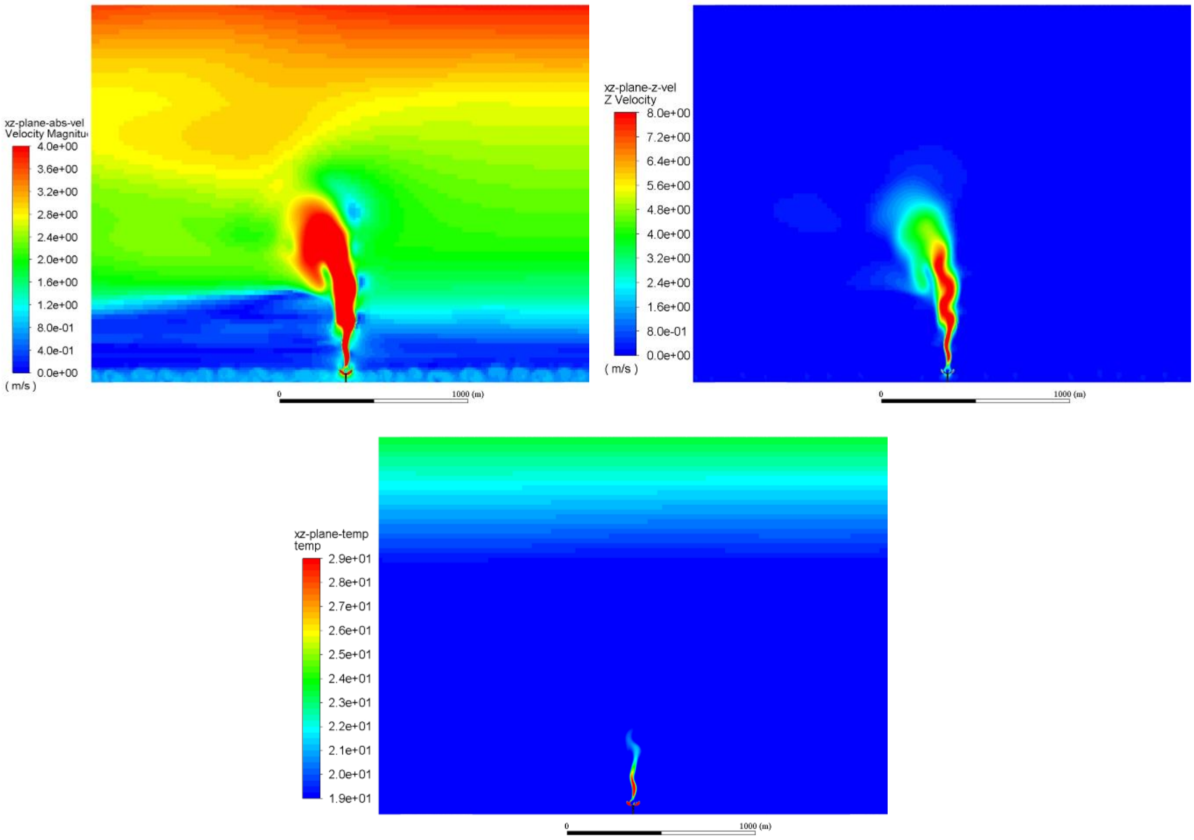


Figure 45. Contour plot in x-z plane through the stack centre for velocity magnitude (upper left), vertical velocity (upper right), and temperature (bottom) - 'Combined' wind case at analysed simulation time.

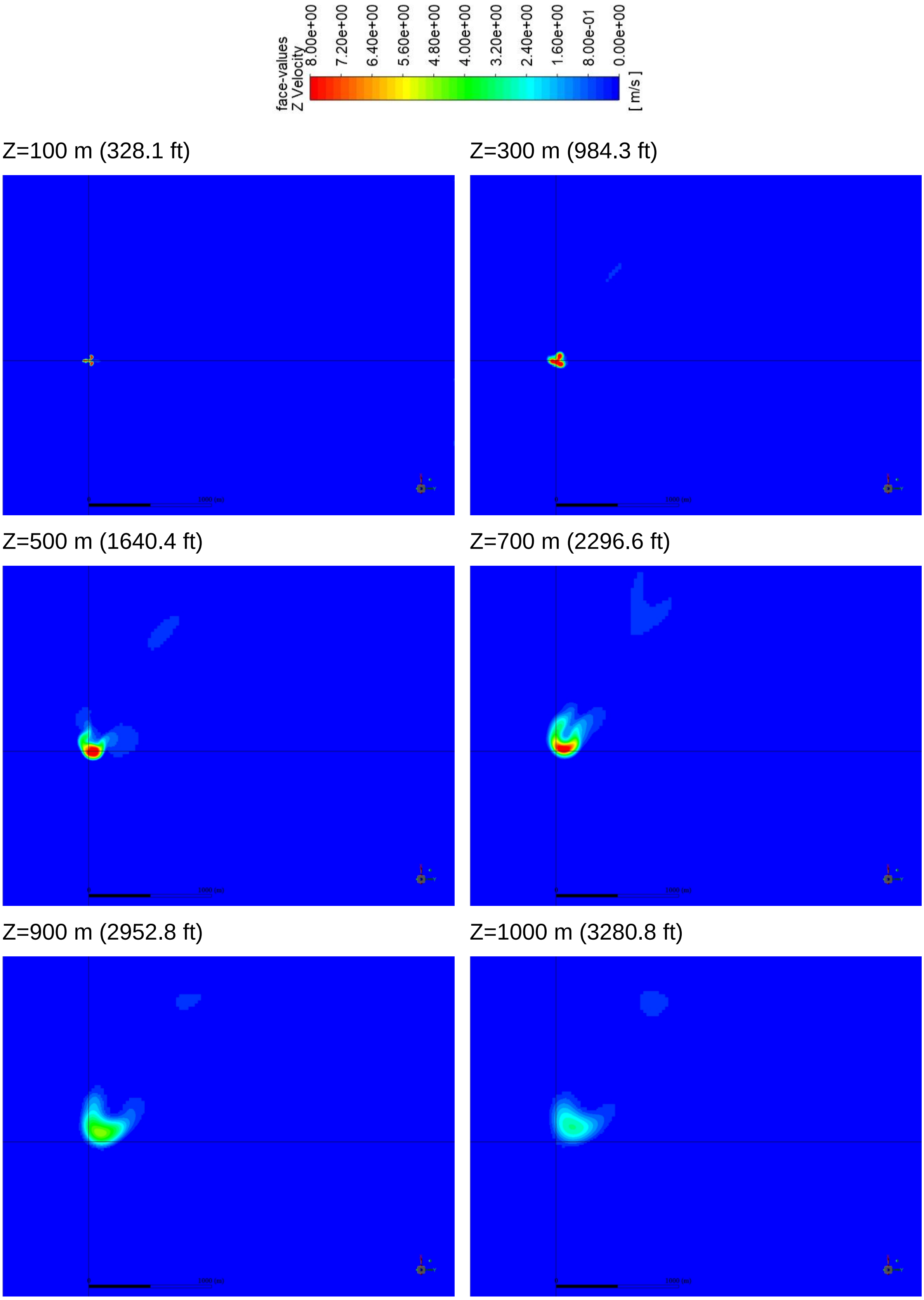


Figure 46. Contour plot of vertical velocity in plan at different horizontal plane heights - 'Combined' wind case at analysed simulation time. Black lines define the stack centre.

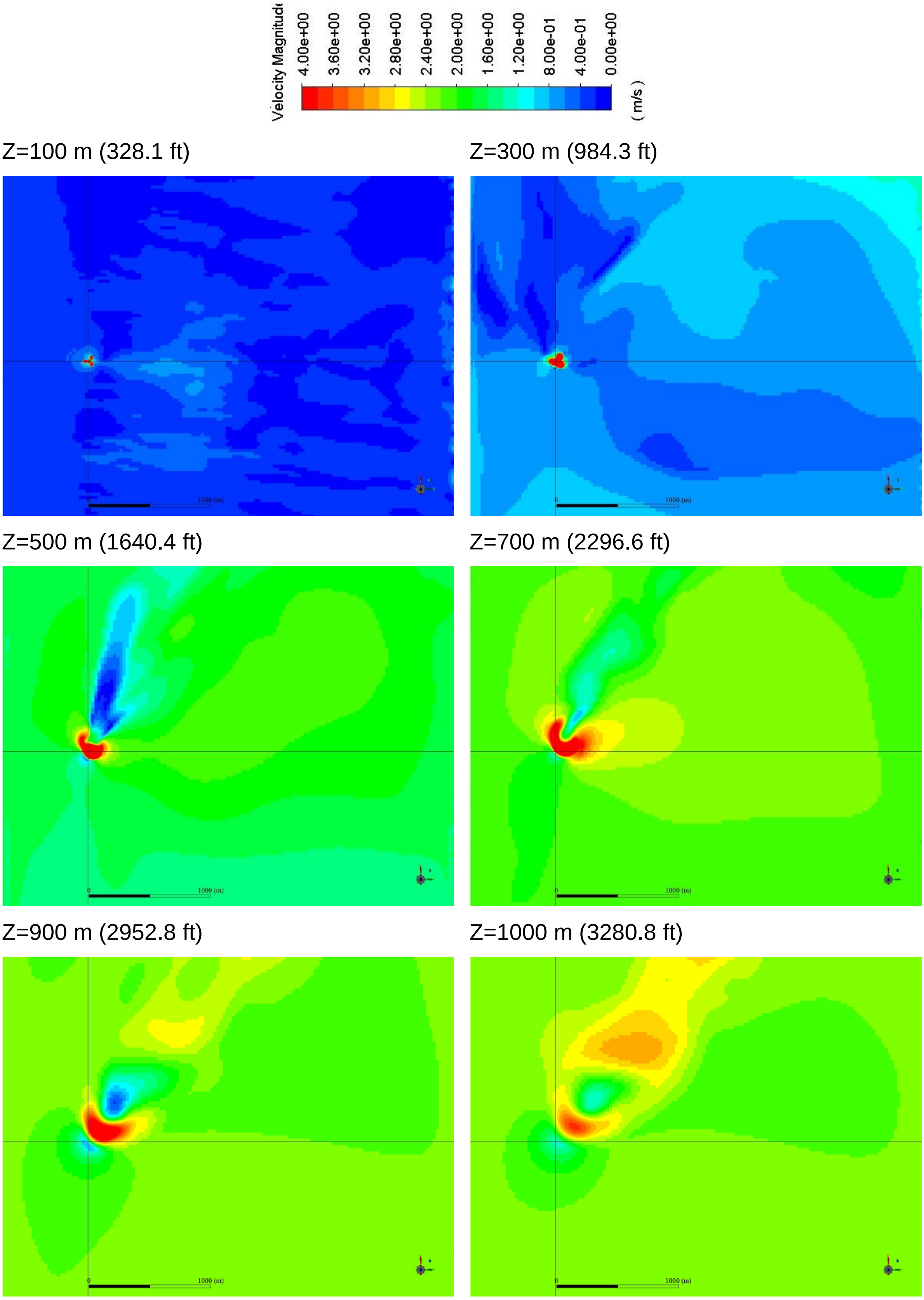


Figure 47. Contour plot of velocity magnitude in plan at different horizontal plane heights - 'Combined' wind case at analysed simulation time. Black lines define the stack centre.

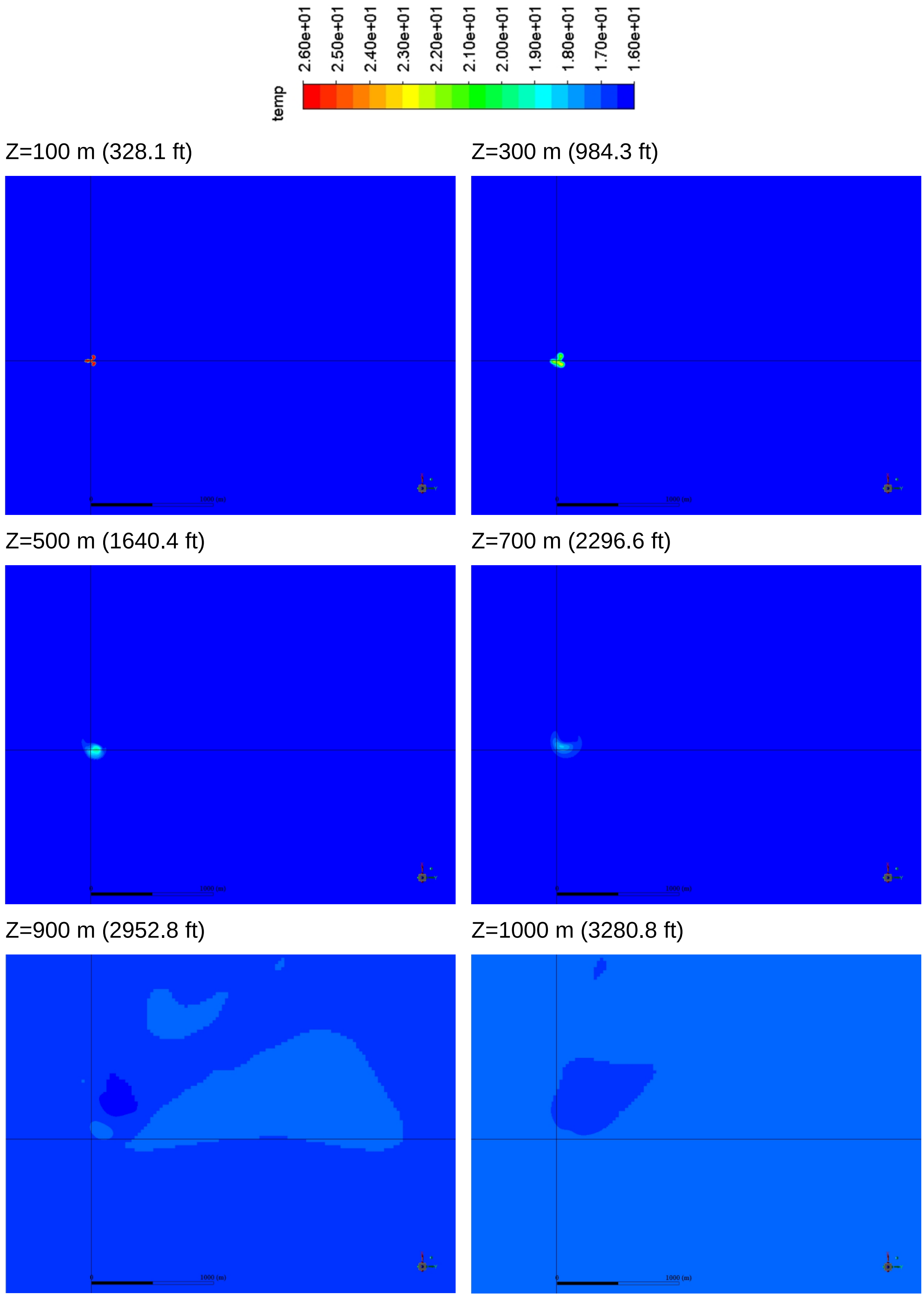


Figure 48. Contour plots of temperature in plan at different heights - 'Combined' wind case at analysed simulation time. Black lines define the stack centre.

APPENDIX B VERIFICATION OF CORRECT IMPLEMENTATION OF THE APPLIED BOUNDARY CONDITIONS

This section is to verify the correct implementation of the essential applied boundary conditions like wind speed, direction, and temperature, as well as the stack characteristics (mass flow rate and temperature) as listed in Table 5 and Table 6. The validation has been done for all different wind scenarios as given in section B.1. to B.3. respectively.

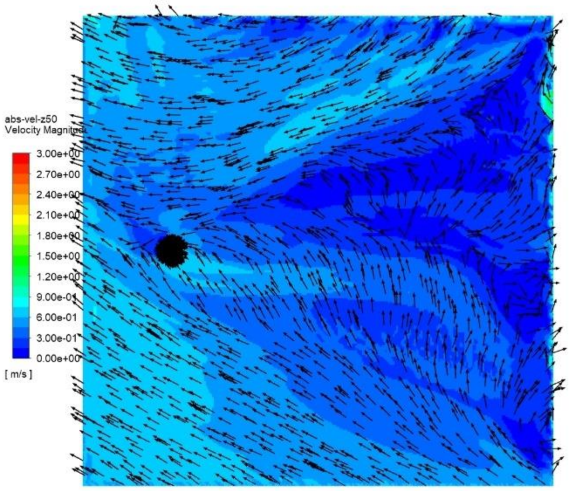
Figure 49, Figure 58 and Figure 67 illustrate the implementation of the wind field in the computational domain based on contour plots of velocity magnitude and normalised velocity vectors (black) at different heights. It is clear that the wind direction is maintained less accurately where the wind speed is very low, and the wind direction changes quickly in elevation.

Vertical lines (from ground level to 2000 m) at several points up- and downstream of the stack have been introduced to evaluate the correct implementation of the wind profile as well as to demonstrate that the wind profile is maintained. Figure 50, Figure 59 and Figure 68 illustrate the different positions of the vertical lines in the domain for the individual cases, respectively. The velocity and temperature profiles in Figure 51 to Figure 54, Figure 60 to Figure 63 and Figure 69 to Figure 72, clearly show that the applied wind profile is influenced by the plume, but is maintained far away from the plume region. The plume can simply be seen as an obstacle that the flow must go around. In addition, the temperature profiles also verify the applied temperature at the ground and the top of the domain.

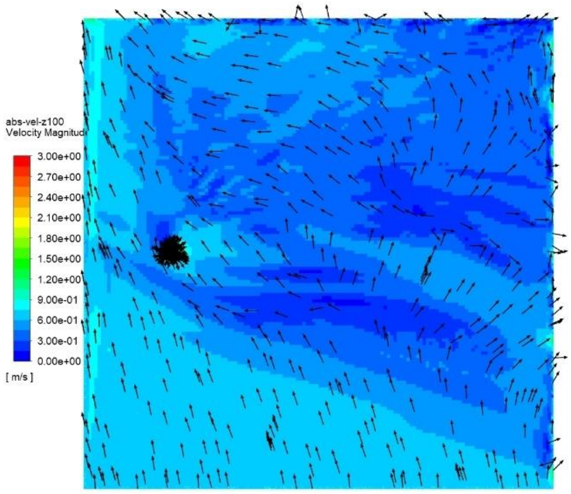
The implementation of the correct stack parameters is verified in Figure 55 to Figure 57, Figure 64 to Figure 66 and Figure 73 to Figure 75. The vertical temperature distribution is also shown in Figure 14, Figure 15, Figure 32, Figure 33, Figure 44 and Figure 45. Horizontal temperature plots in different levels are also shown in Figure 18, Figure 36 and Figure 48.

B.1. 'Initial' Wind Case (Wind and Temperature Profile: 20140703_10)

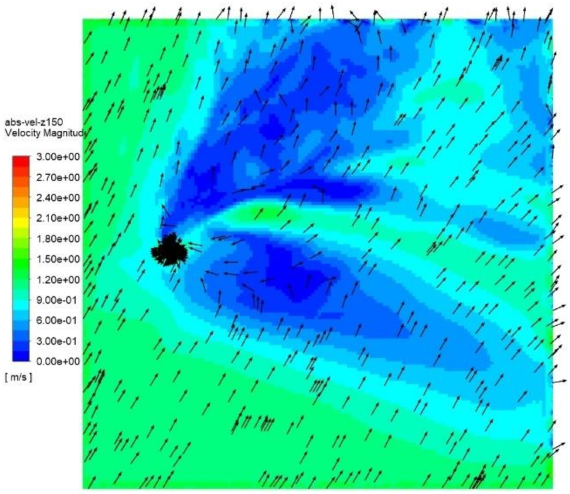
Z = 50 m (164 ft)



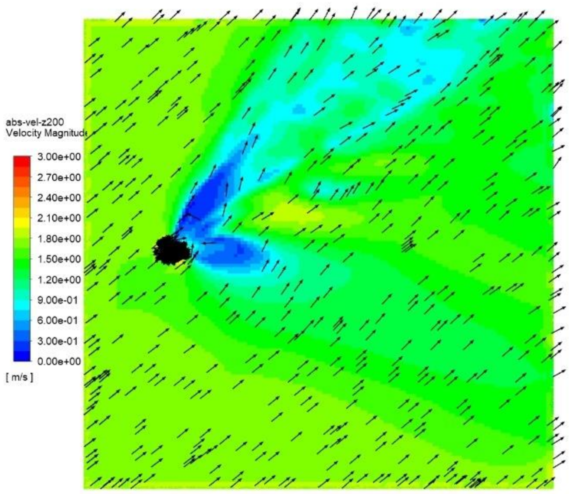
Z = 100 m (328 ft)



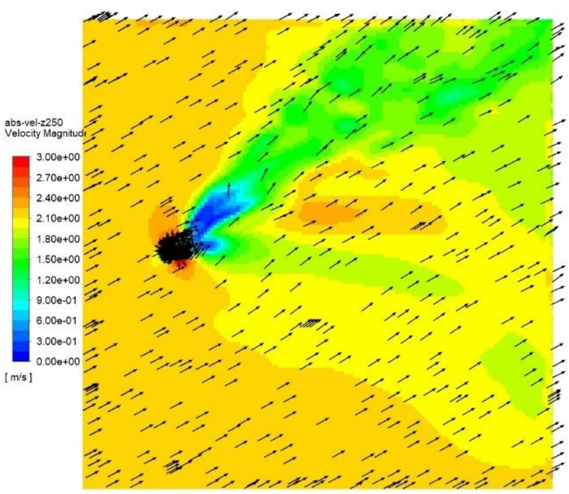
Z = 150 m (656 ft)



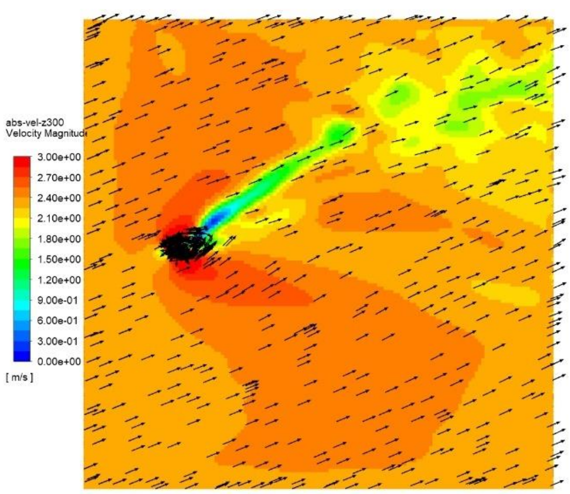
Z = 200 m (492 ft)



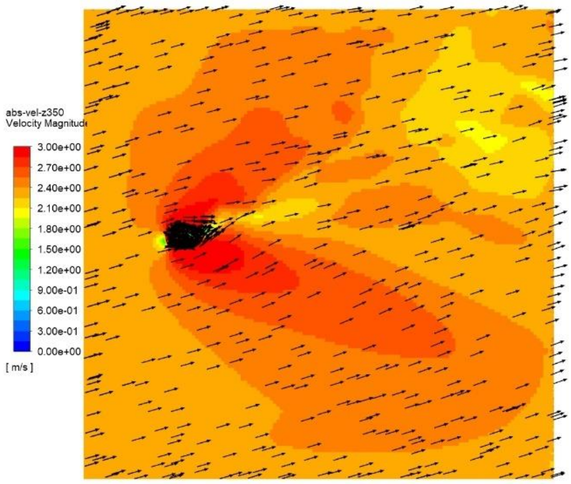
Z = 250 m (820 ft)



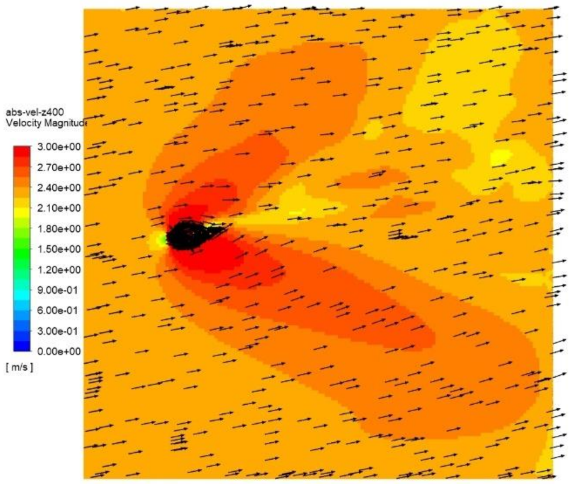
Z = 300 m (984 ft)



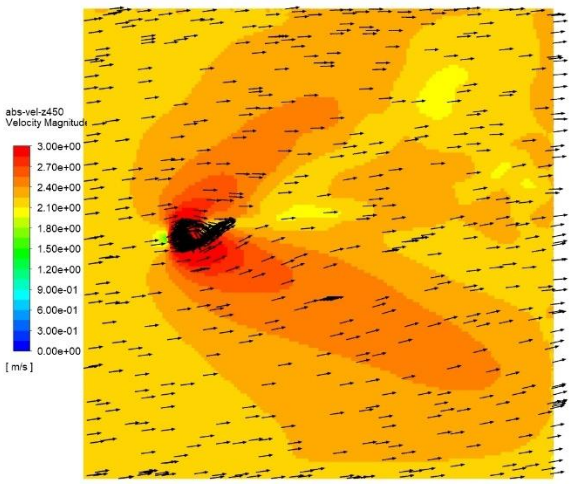
Z = 350 m (1148 ft)



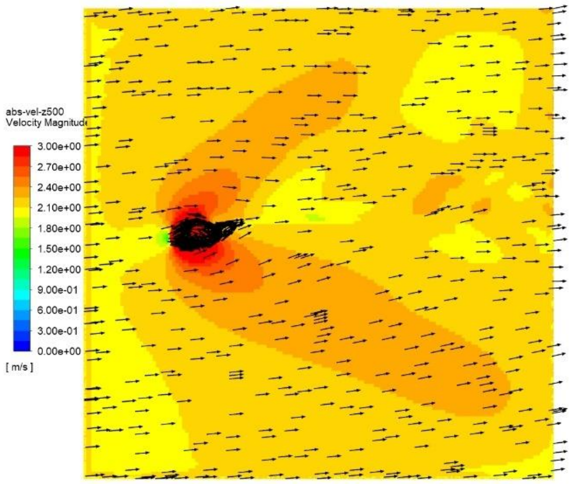
Z = 400 m (1312 ft)



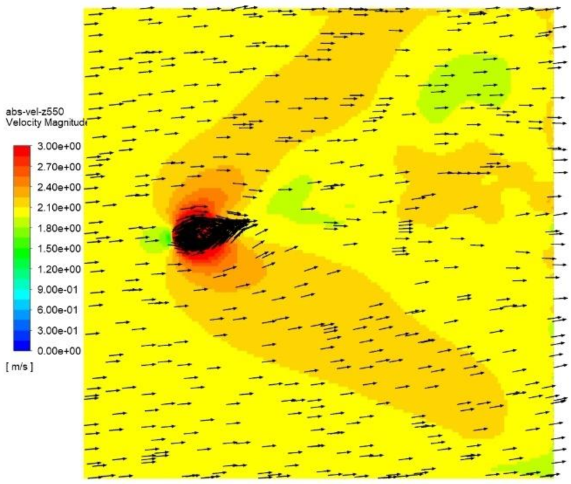
Z = 450 m (1476 ft)



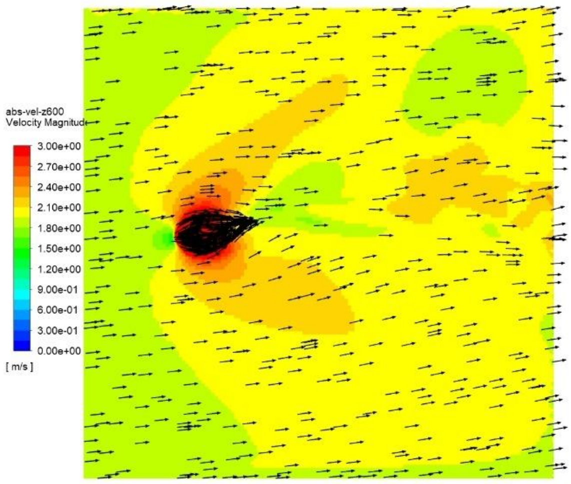
Z = 500 m (1640 ft)



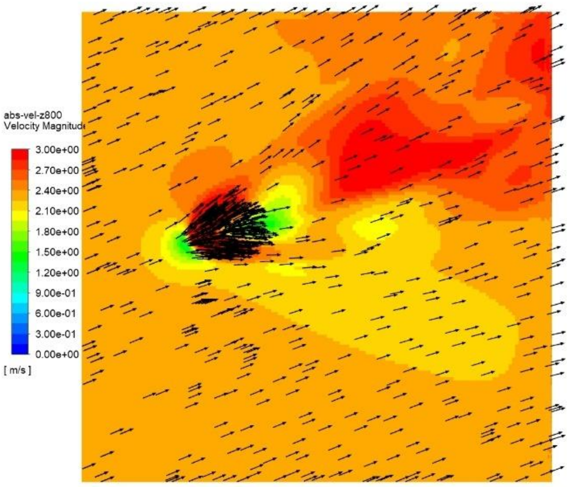
Z = 550 m (1804 ft)



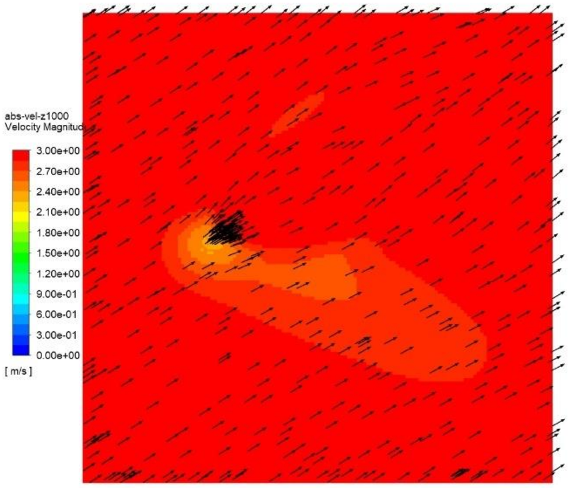
Z = 600 m (1969 ft)



Z = 800 m (2625 ft)



Z = 1000 m (3281 ft)



Z = 1500 m (4921 ft)

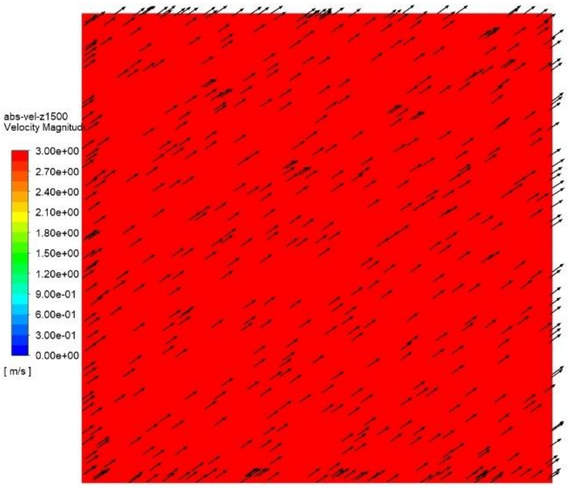


Figure 49. Contour plots of velocity magnitude with normalised velocity vectors at different heights - 'Initial' wind case.

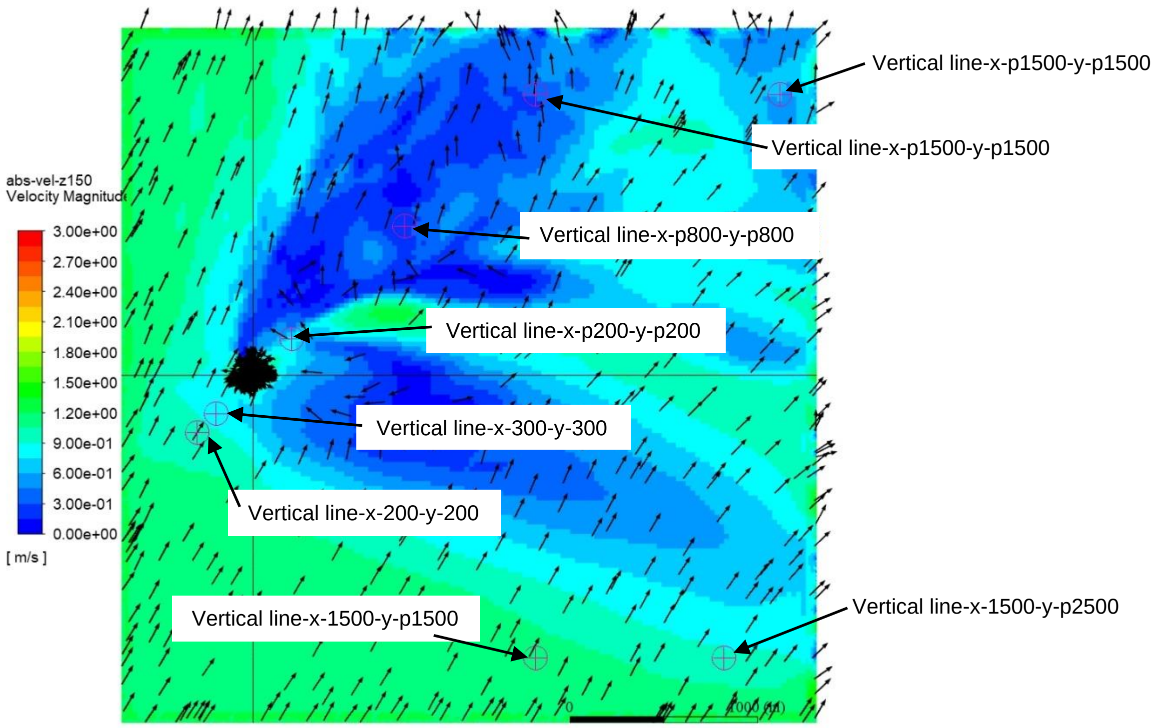


Figure 50. Position of vertical sample lines (from ground level to 2000 m) for analysing the correct implementation of the wind profile - 'Initial' wind case.

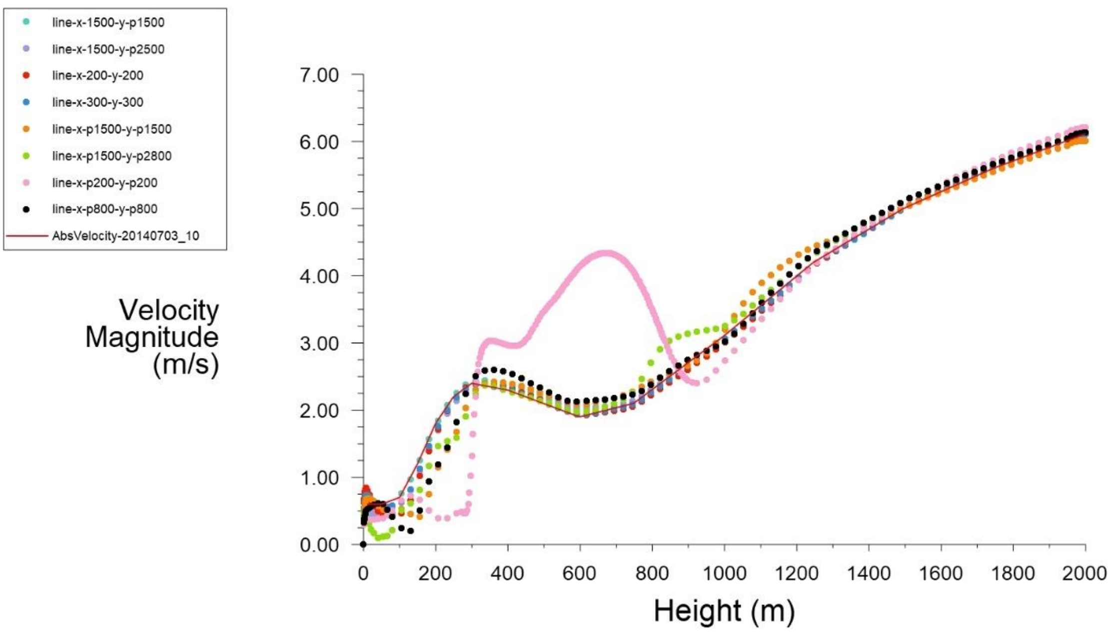


Figure 51. Velocity magnitude along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 50). Red line demonstrates the applied wind profile according to Figure 1 - 'Initial' wind case.

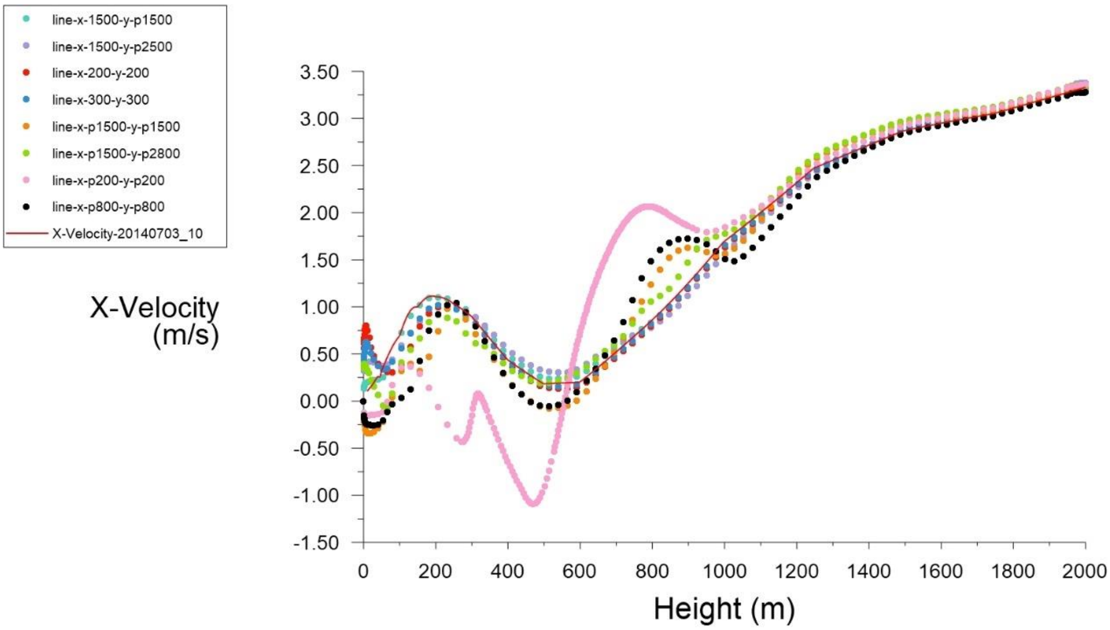


Figure 52. Velocity in the x-direction of the domain along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 50). Red line demonstrates the applied wind profile according to Figure 1 - 'Initial' wind case.

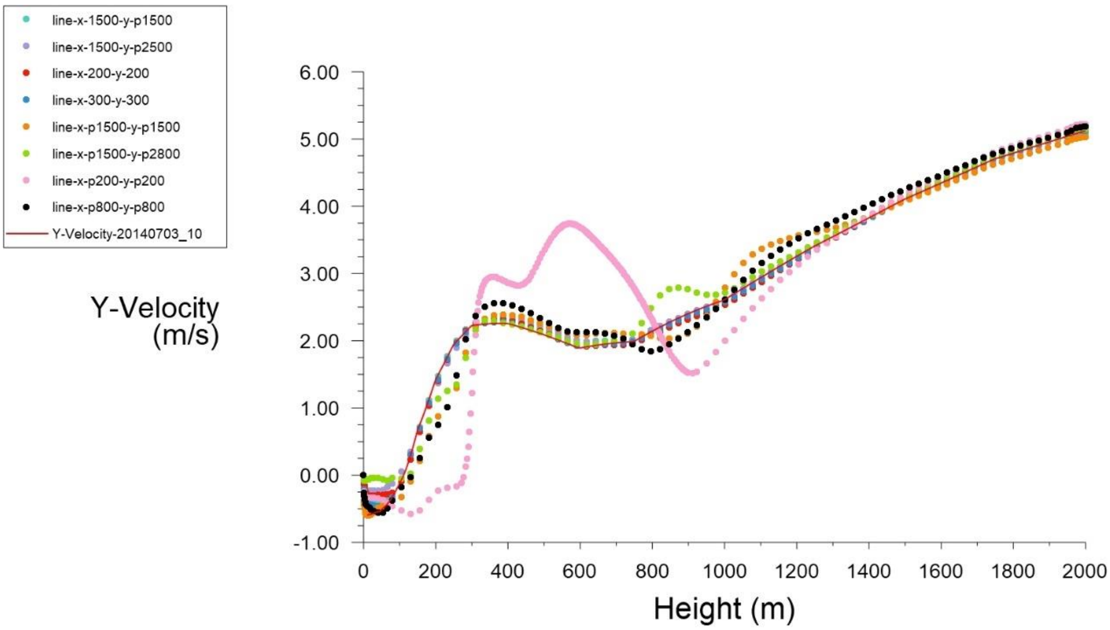


Figure 53. Velocity in the y-direction of the domain along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 50). Red line demonstrates the applied wind profile according to Figure 1 - 'Initial' wind case.

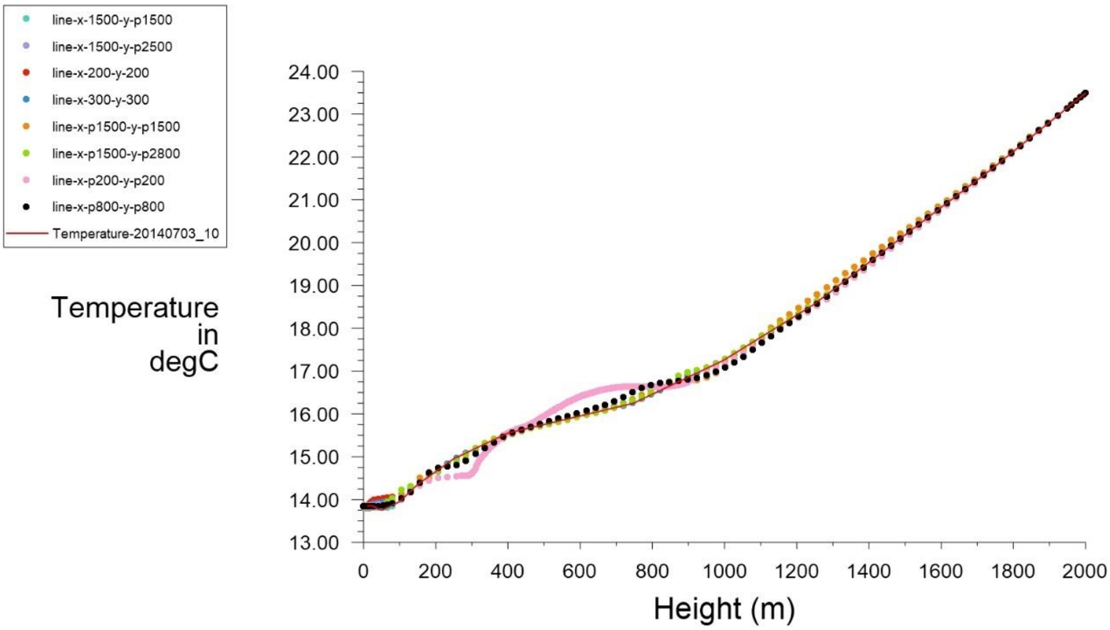


Figure 54. Temperature along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 50). Red line demonstrates the applied wind profile according to Figure 1 - 'Initial' wind case.

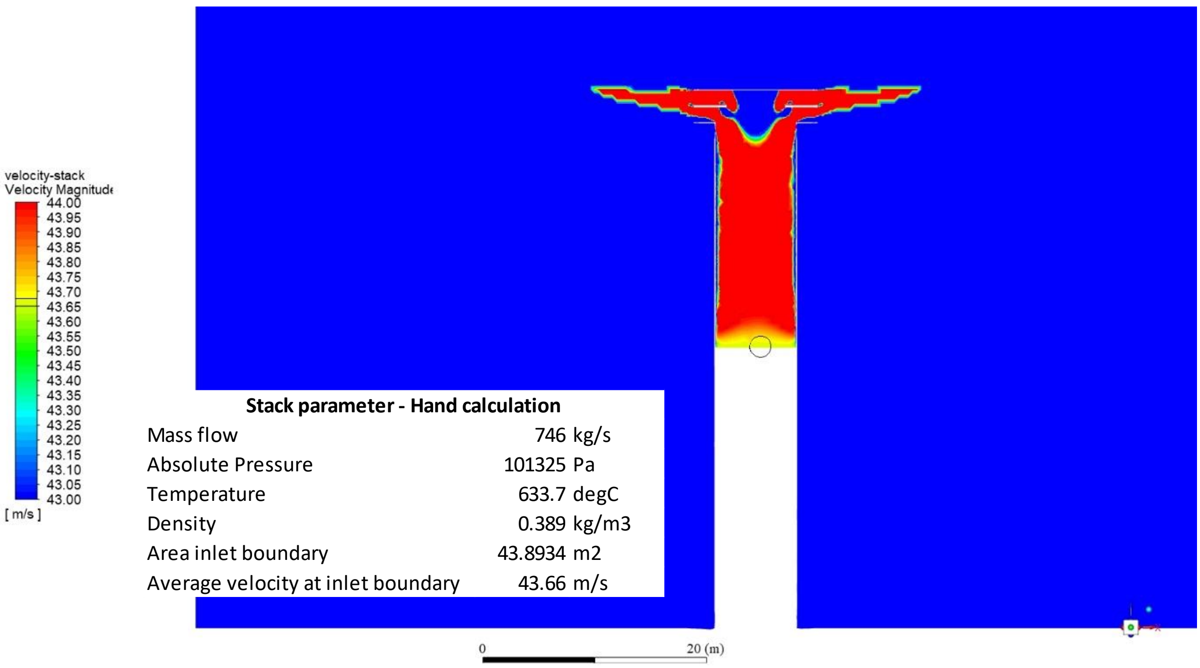


Figure 55. Contour plot of velocity magnitude through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - 'Initial' wind case.

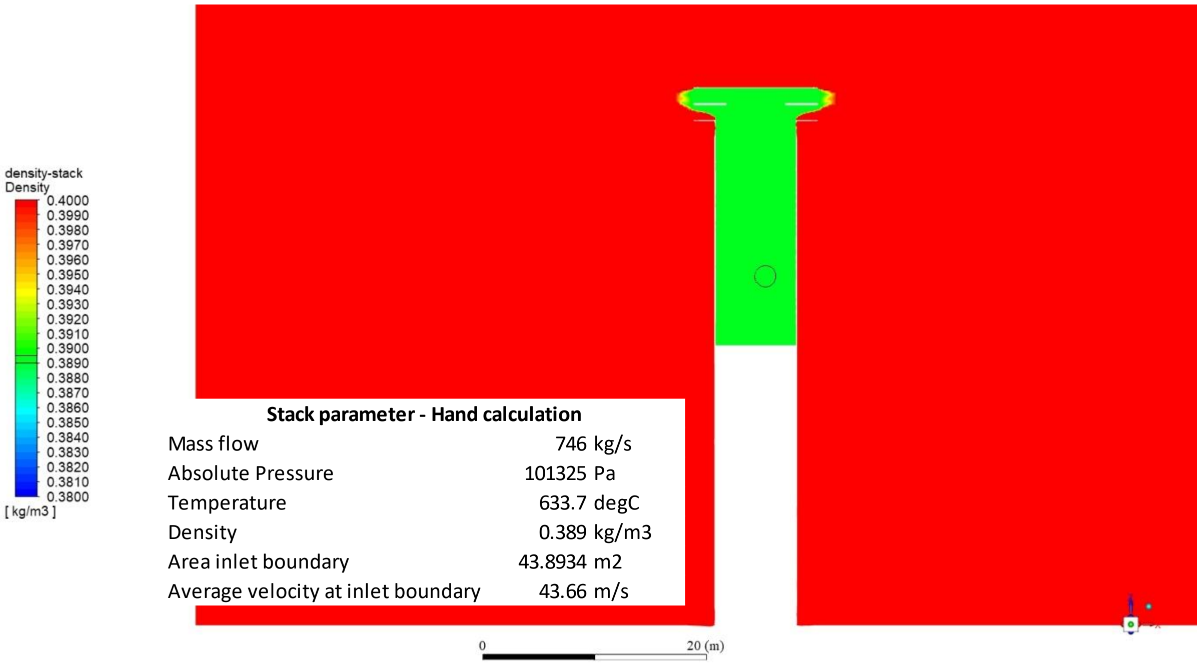


Figure 56. Contour plot of air density through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - 'Initial' wind case.

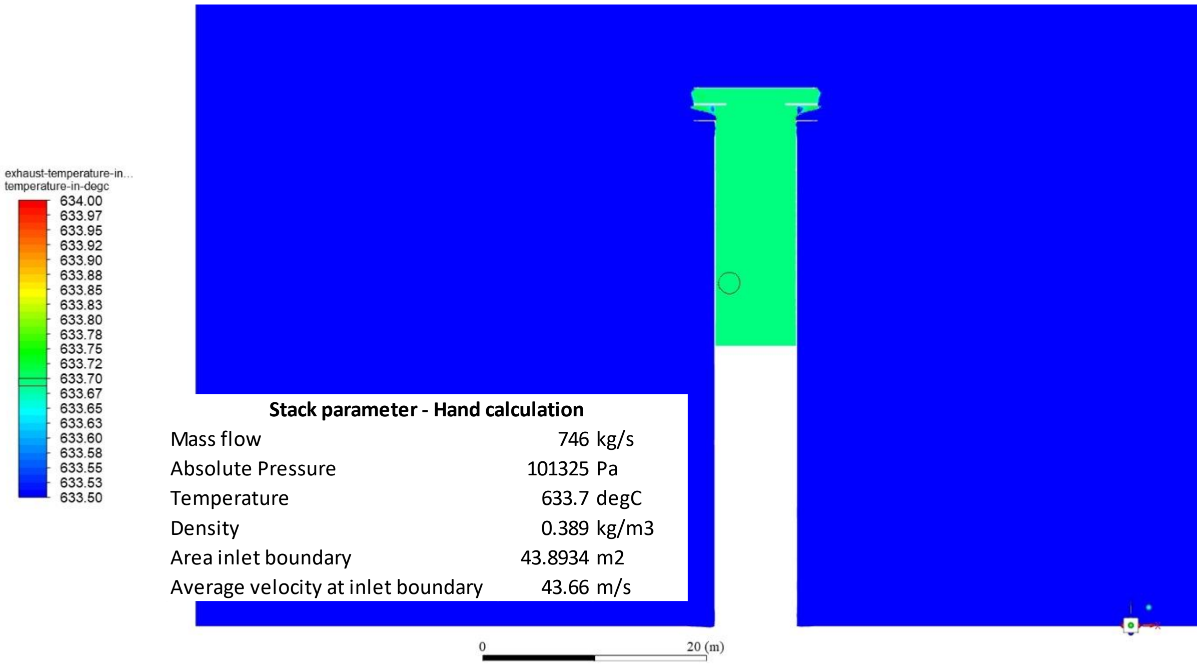
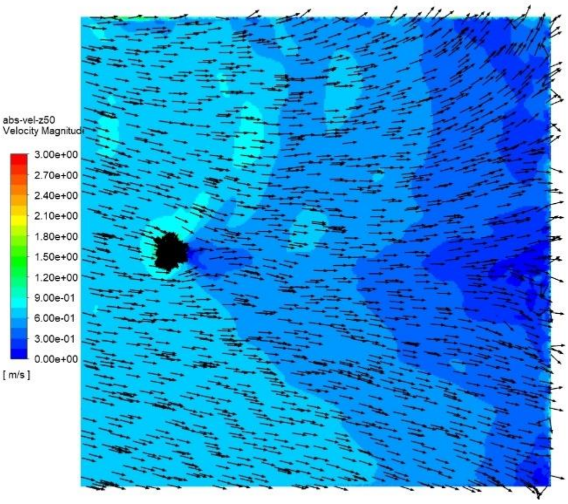


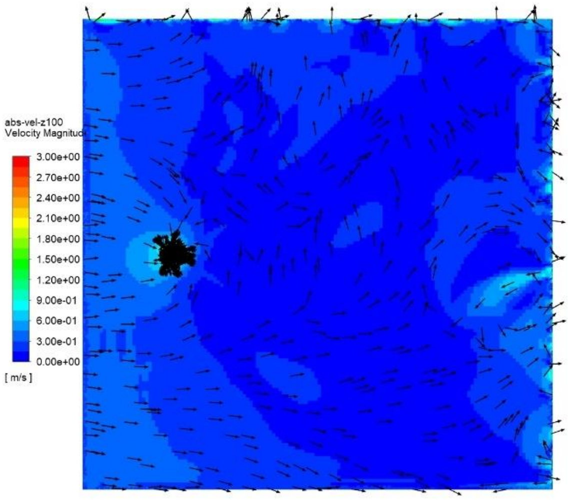
Figure 57. Contour plot of temperature in °C through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - 'Initial' wind case.

B.2. Calm Wind Case (Wind and Temperature Profile: 20150308 – Calm)

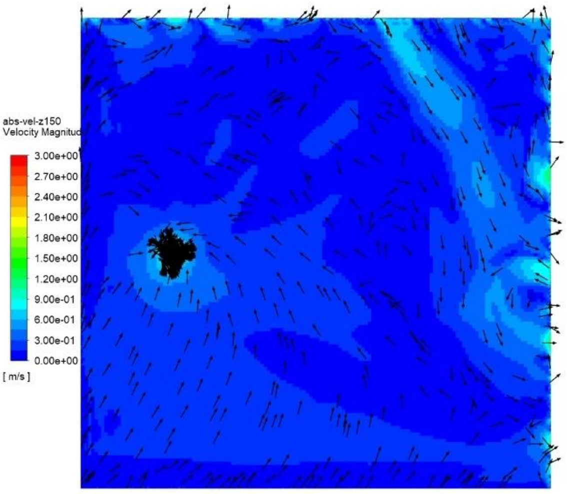
Z = 50 m (164 ft)



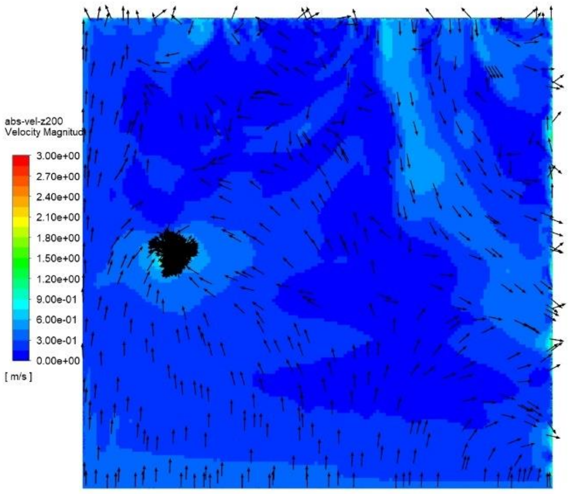
Z = 100 m (328 ft)



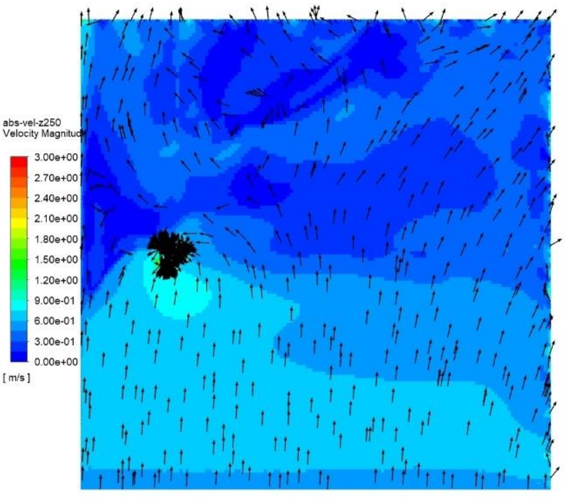
Z = 150 m (656 ft)



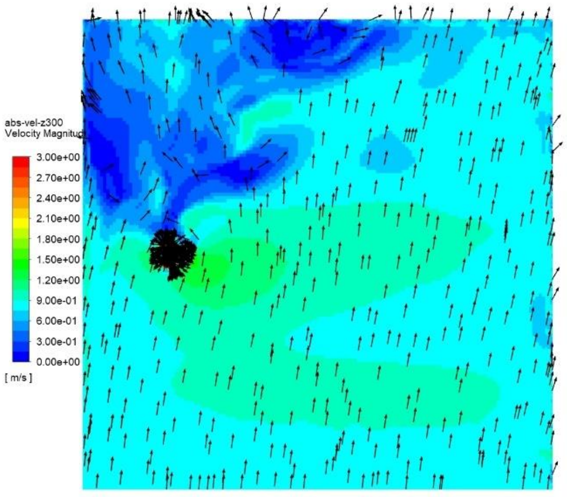
Z = 200 m (492 ft)



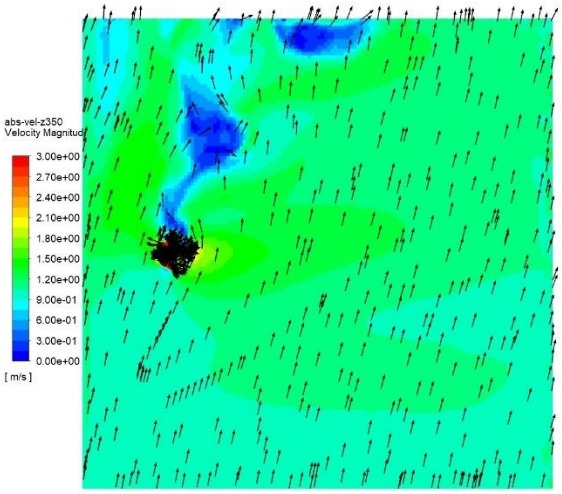
Z = 250 m (820 ft)



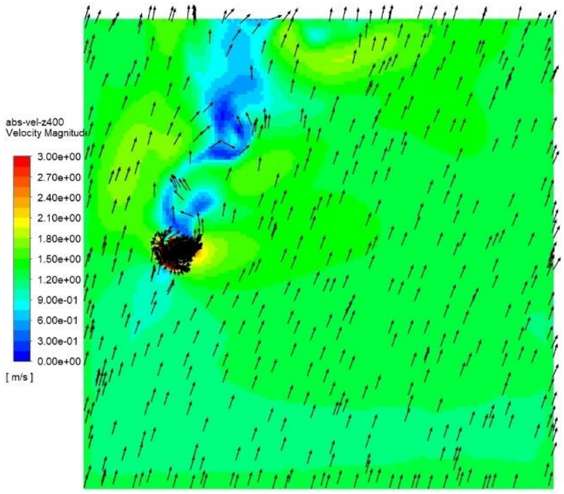
Z = 300 m (984 ft)



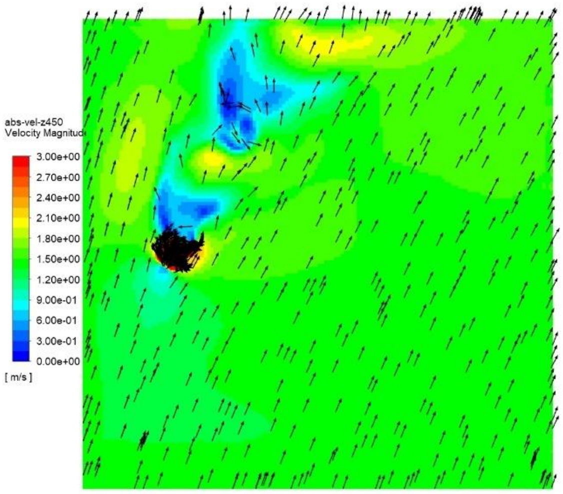
Z = 350 m (1148 ft)



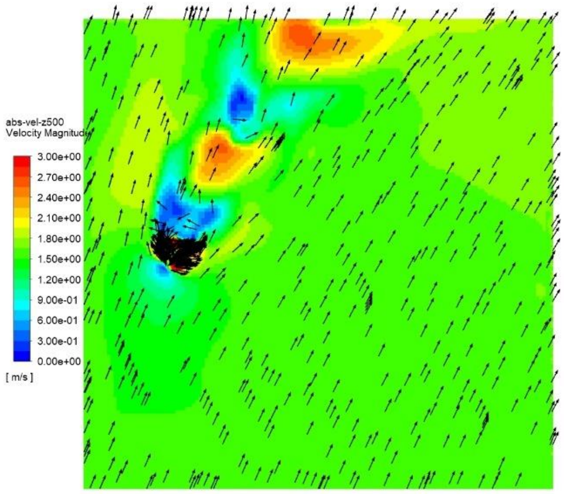
Z = 400 m (1312 ft)



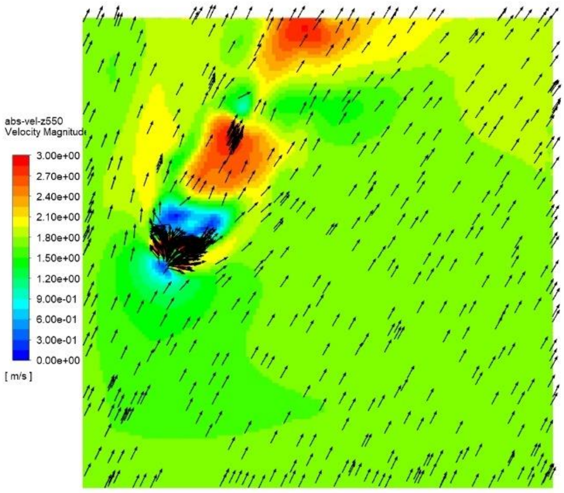
Z = 450 m (1476 ft)



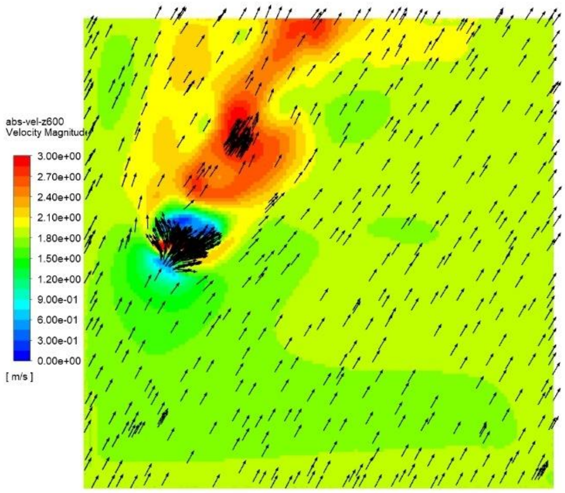
Z = 500 m (1640 ft)



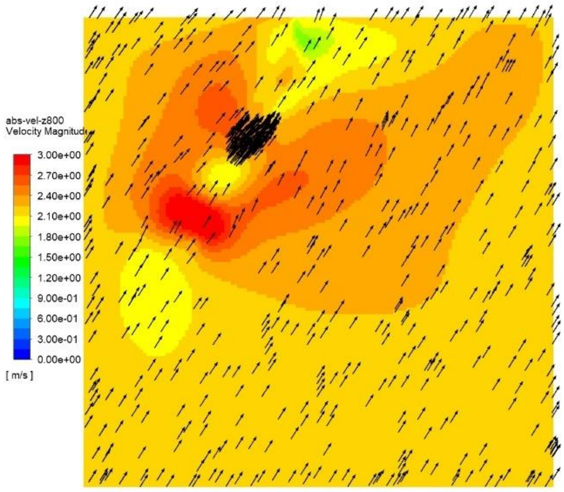
Z = 550 m (1804 ft)



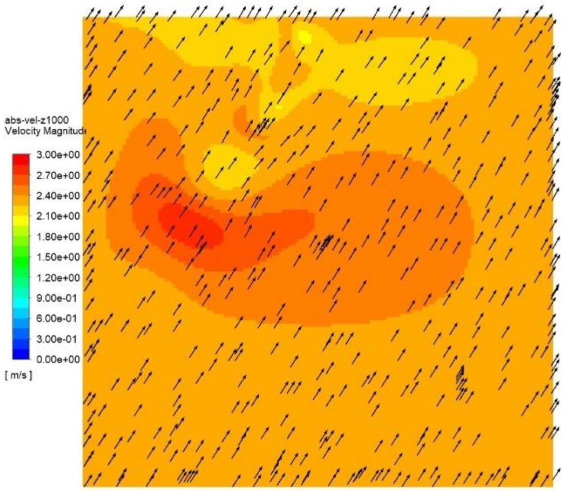
Z = 600 m (1969 ft)



Z = 800 m (2625 ft)



Z = 1000 m (3281 ft)



Z = 1500 m (4921 ft)

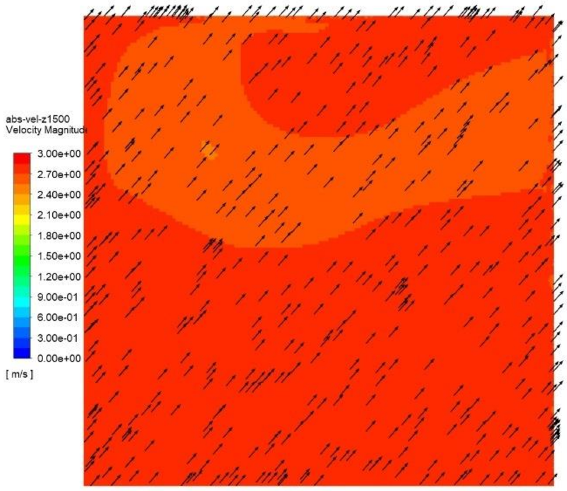


Figure 58. Contour plots of velocity magnitude with normalised velocity vectors at different heights - Calm wind case.

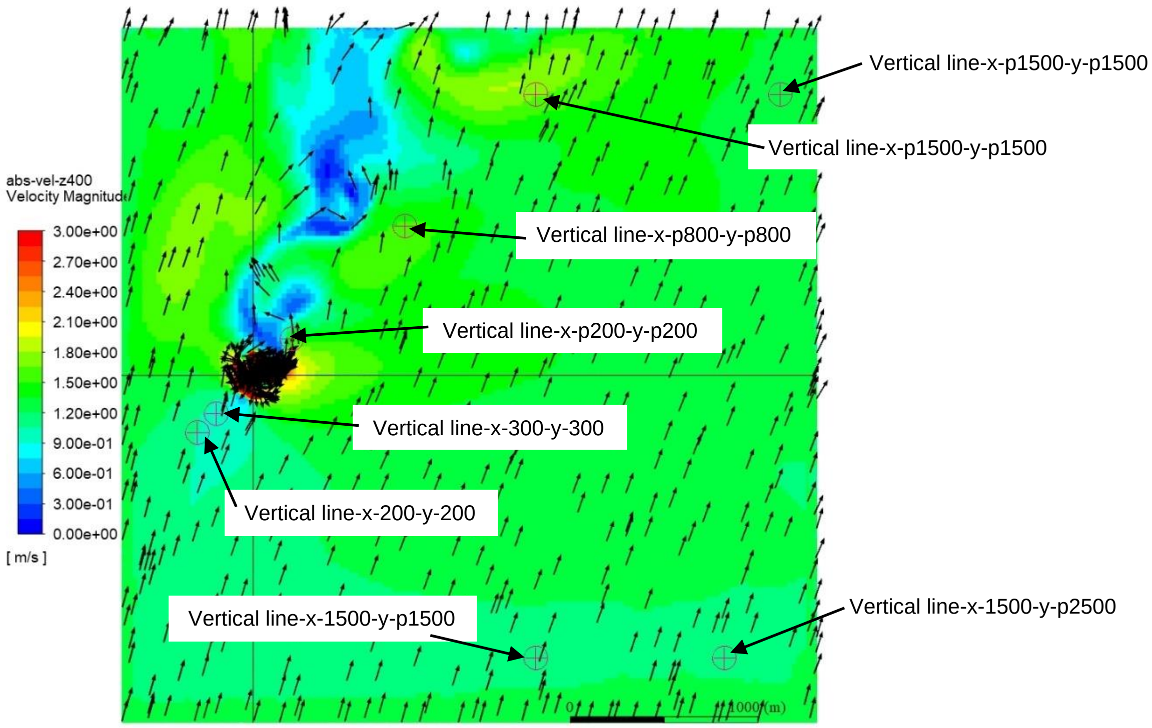


Figure 59. Position of vertical sample lines (from ground level to 2000 m) for analysing the correct implementation of the wind profile - Calm wind case.

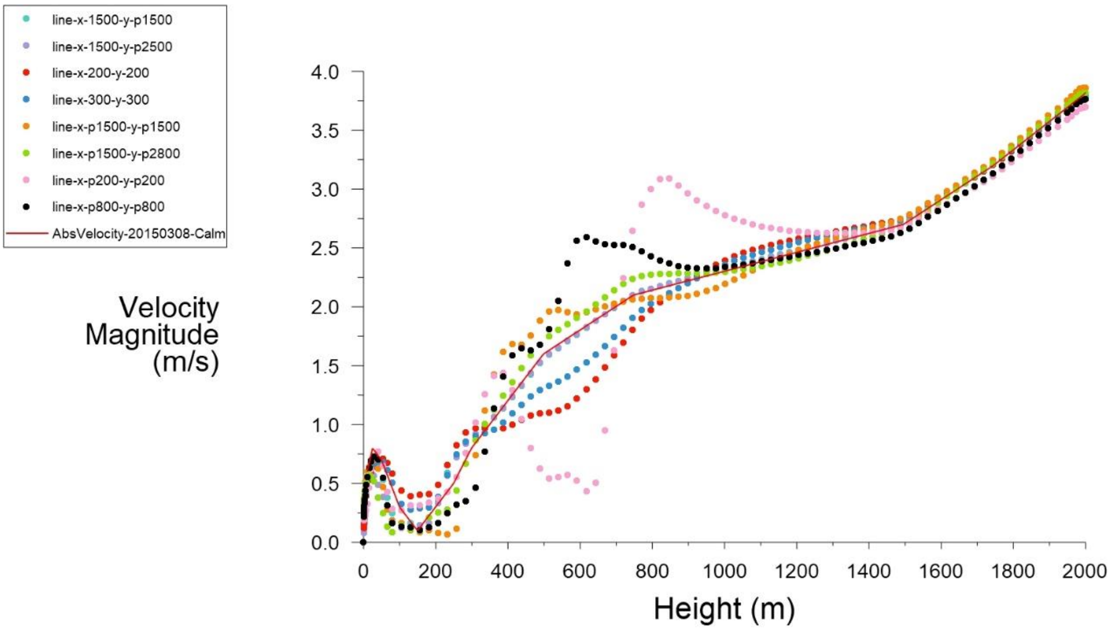


Figure 60. Velocity magnitude along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 59). Red line demonstrates the applied wind profile according to Figure 1 - Calm wind case.

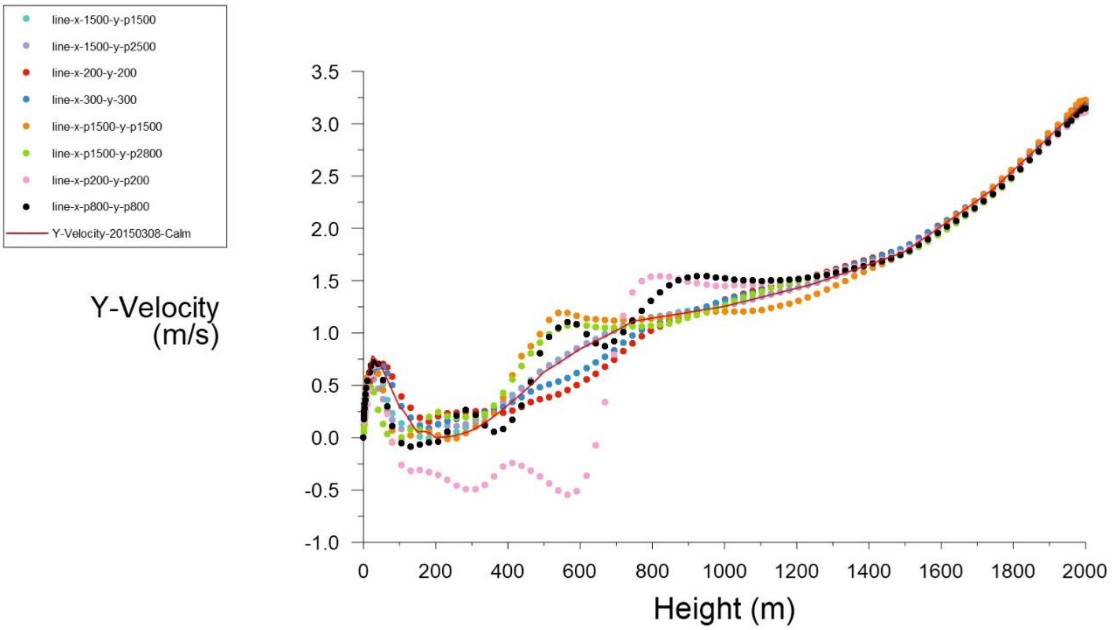


Figure 61. Velocity in the x-direction of the domain along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 59). Red line demonstrates the applied wind profile according to Figure 1 - Calm wind case.

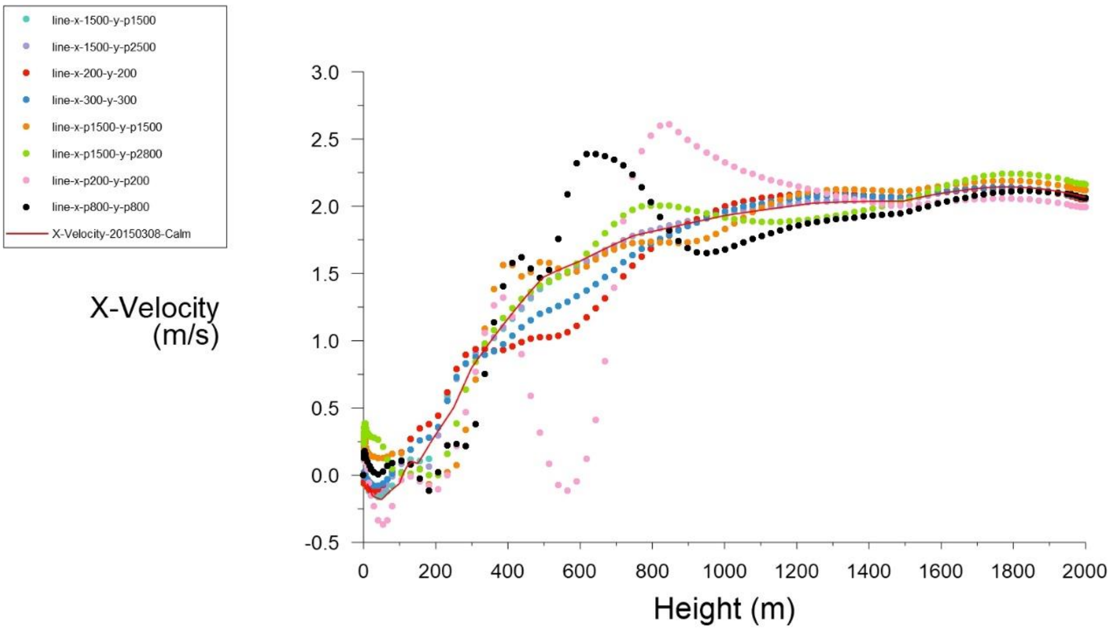


Figure 62. Velocity in the y-direction of the domain along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 59). Red line demonstrates the applied wind profile according to Figure 1 - Calm wind case.

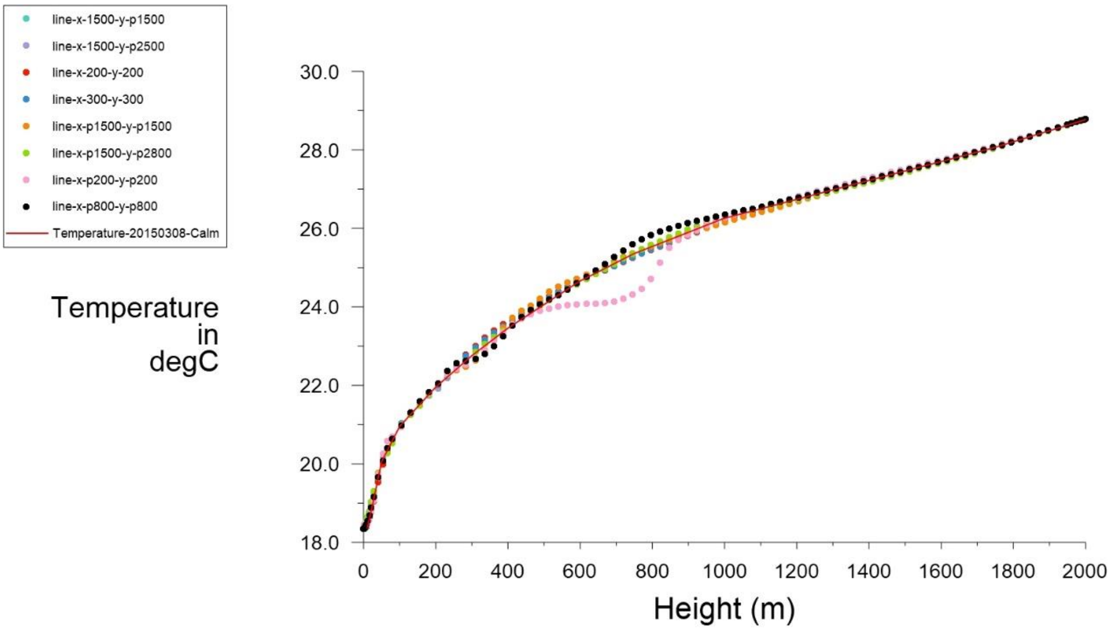


Figure 63. Temperature along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 59). Red line demonstrates the applied wind profile according to Figure 1 - Calm wind case.

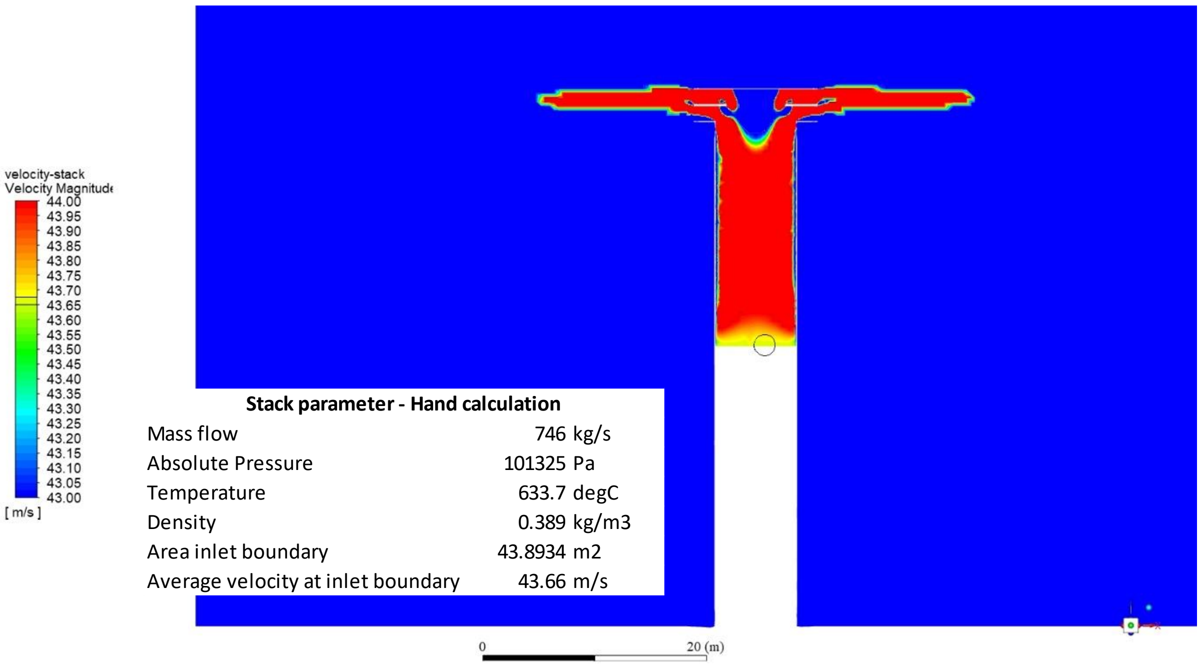


Figure 64. Contour plot of velocity magnitude through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - Calm wind case.

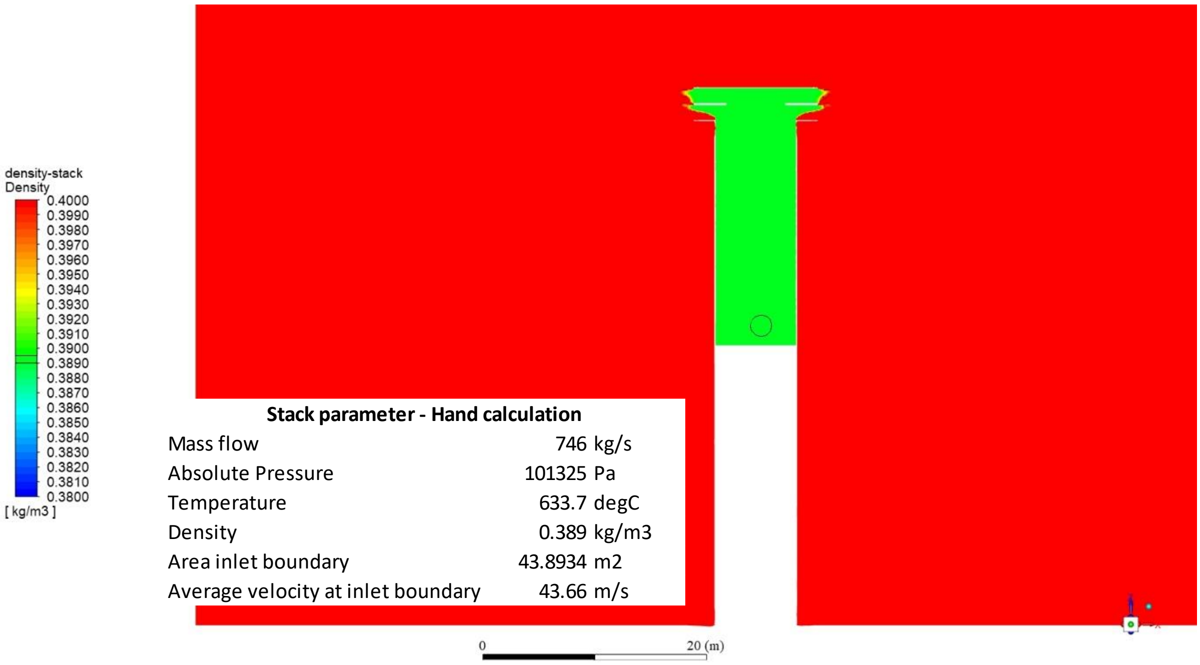


Figure 65. Contour plot of air density through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - Calm wind case.

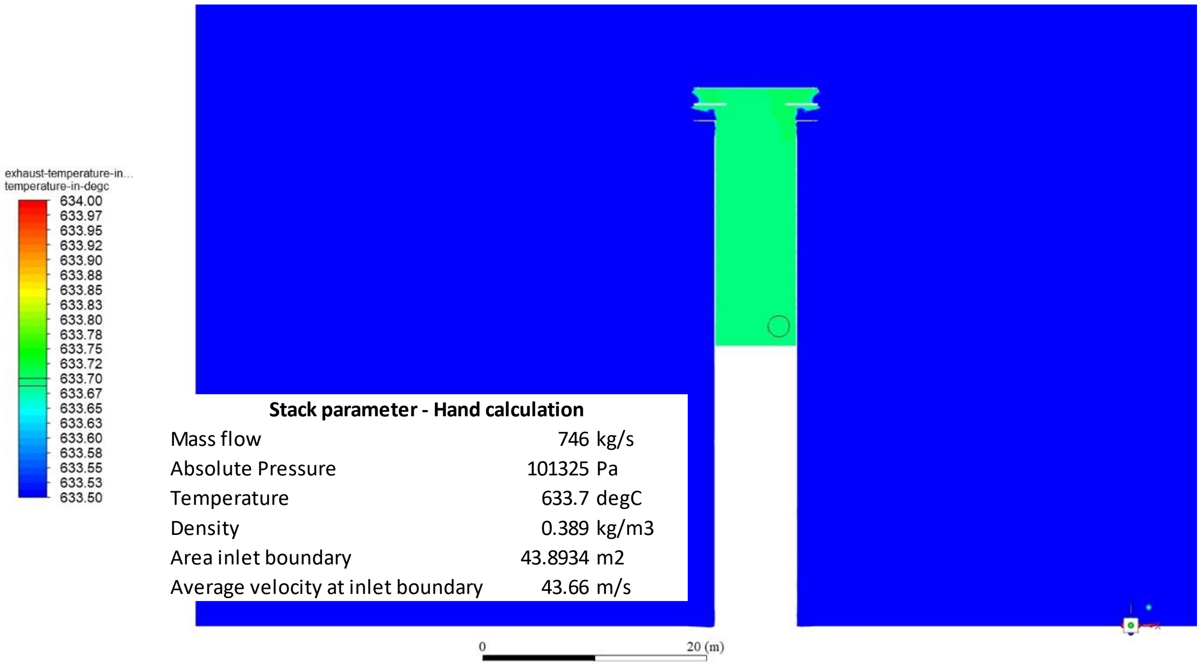
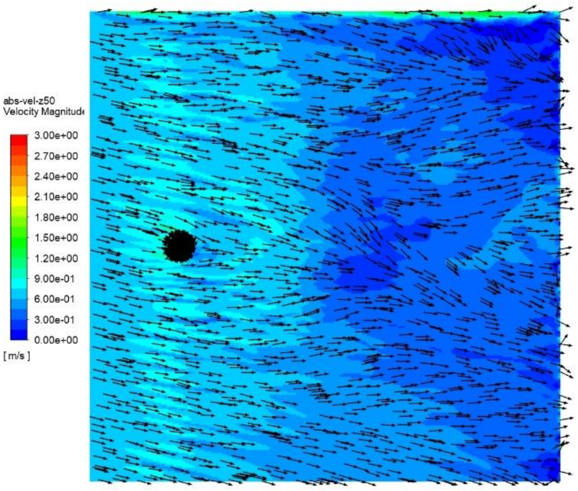


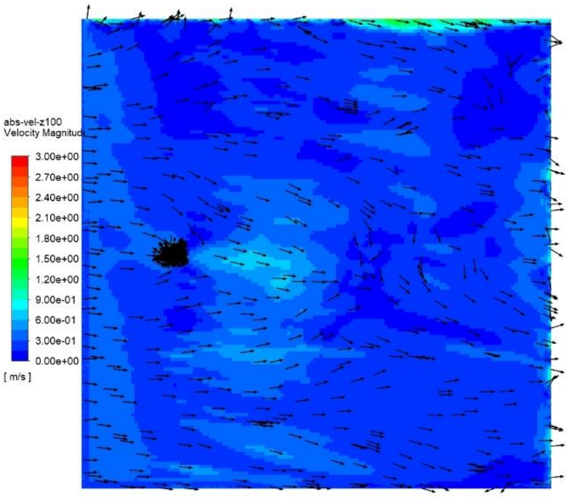
Figure 66. Contour plot of temperature in °C through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - Calm wind case.

B.3. ‘Combined’ Wind Case (Wind profile: 20150308 – Calm and Temperature profile 20140703_10)

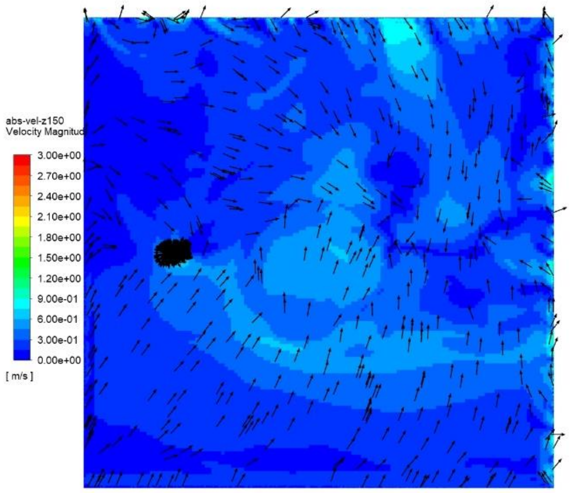
Z = 50 m (164 ft)



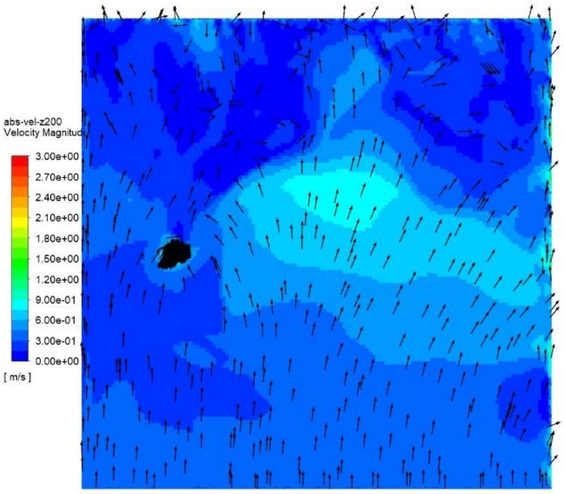
Z = 100 m (328 ft)



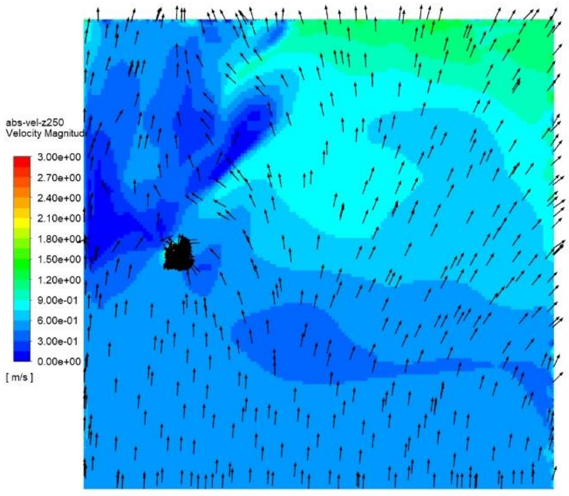
Z = 150 m (656 ft)



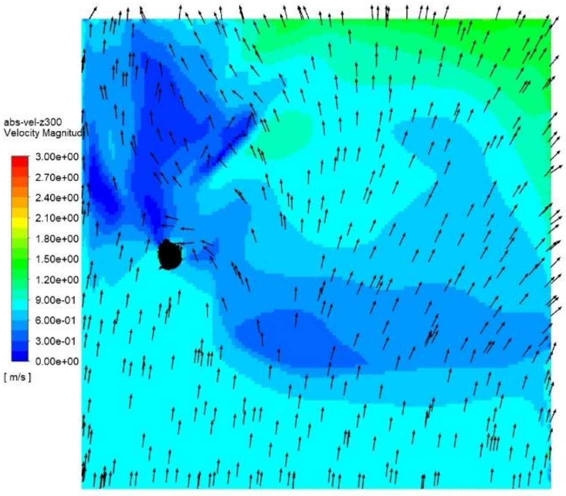
Z = 200 m (492 ft)



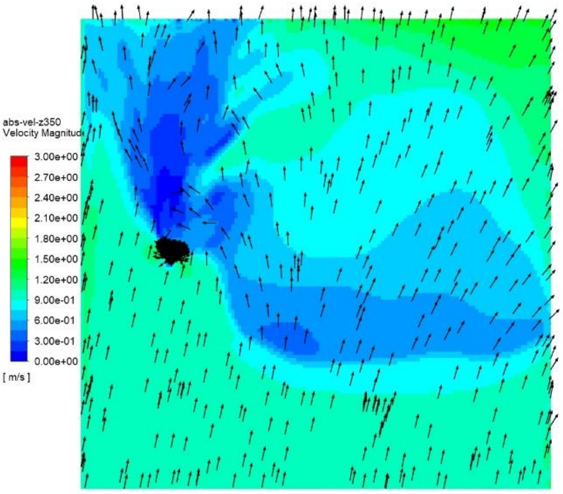
Z = 250 m (820 ft)



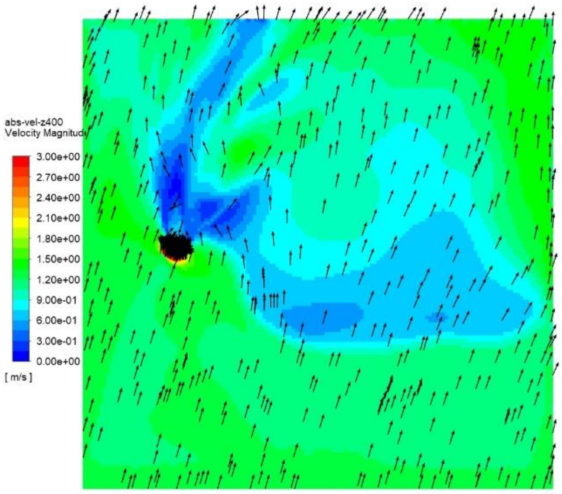
Z = 300 m (984 ft)



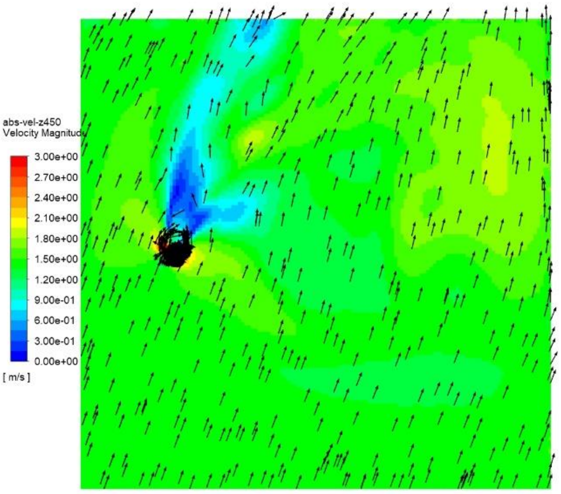
Z = 350 m (1148 ft)



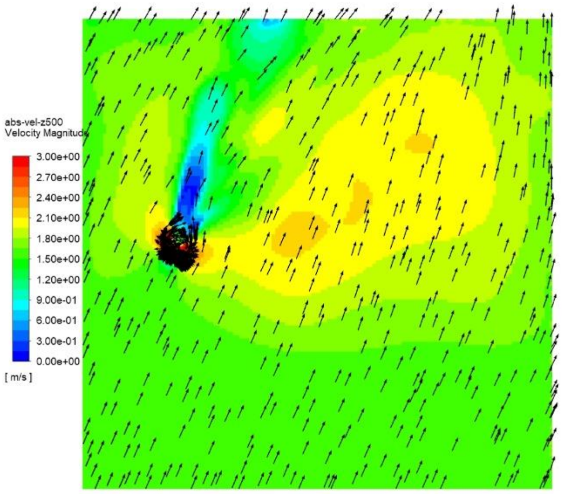
Z = 400 m (1312 ft)



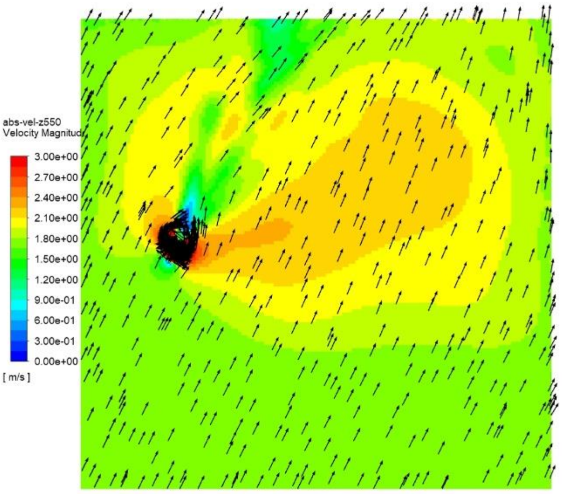
Z = 450 m (1476 ft)



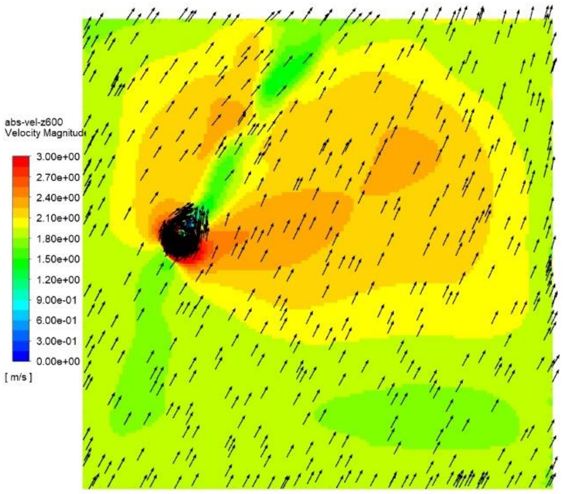
Z = 500 m (1640 ft)



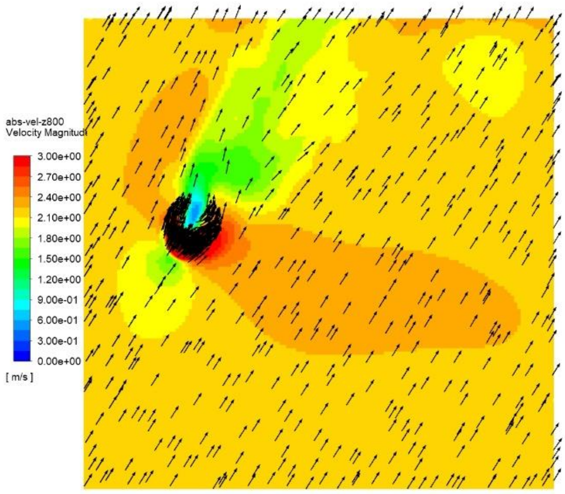
Z = 550 m (1804 ft)



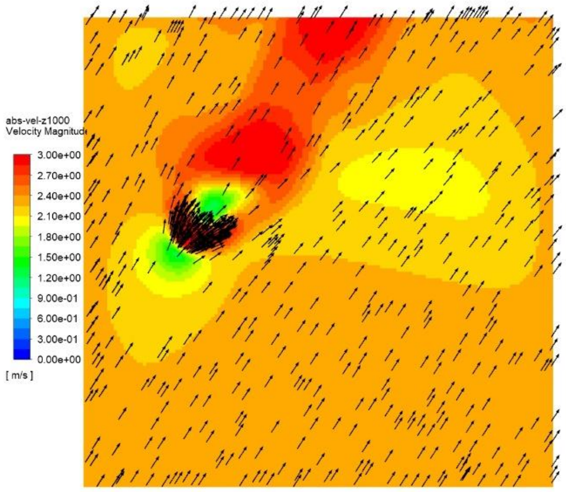
Z = 600 m (1969 ft)



Z = 800 m (2625 ft)



Z = 1000 m (3281 ft)



Z = 1500 m (4921 ft)

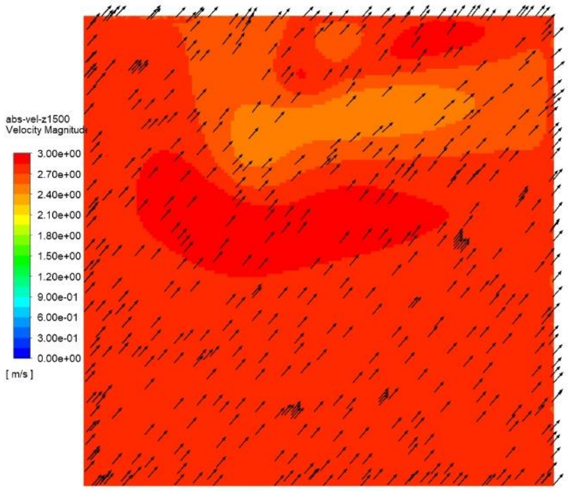


Figure 67. Contour plots of velocity magnitude with normalised velocity vectors at different heights - 'Combined' wind case at analysed simulation time.

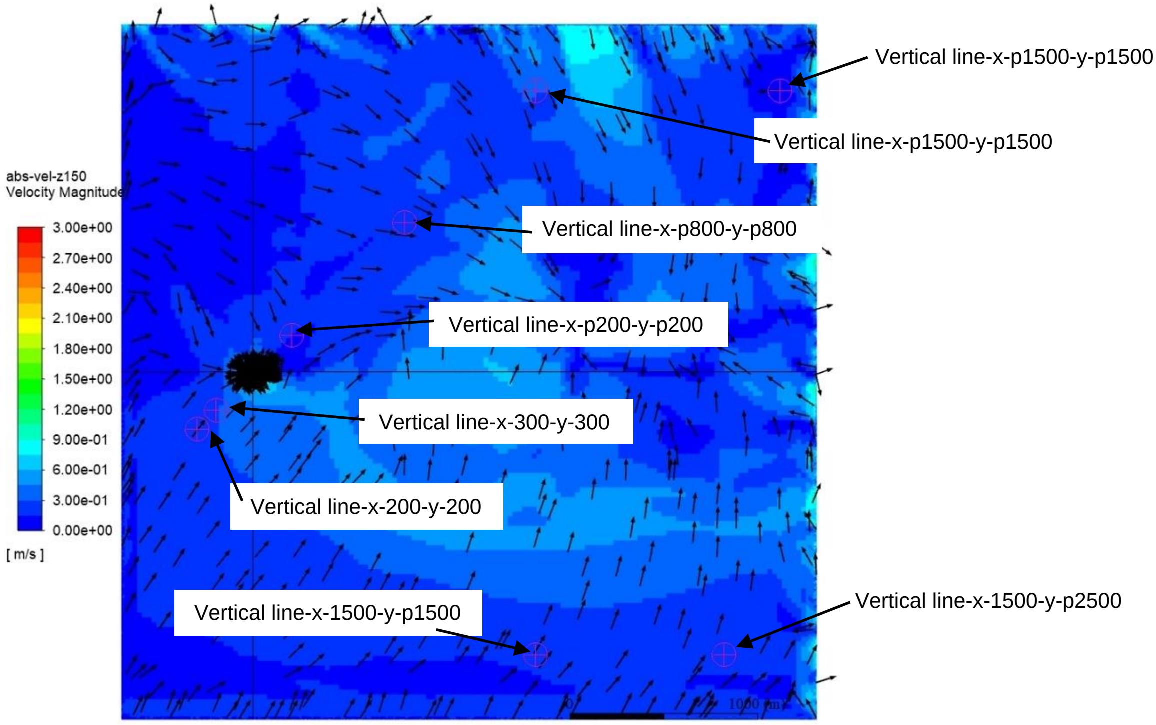


Figure 68. Position of vertical sample lines (from ground level to 2000 m) for analysing the correct implementation of the wind profile – 'Combined' wind case.

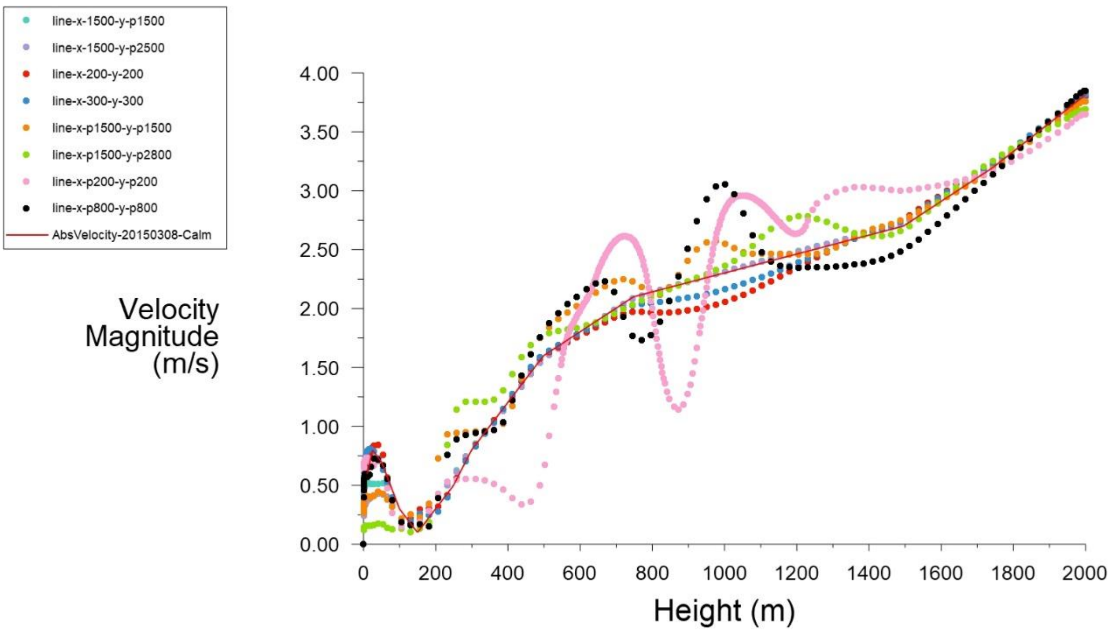


Figure 69. Velocity magnitude along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 68). Red line demonstrates the applied wind profile according to Figure 1 – 'Combiined' wind case at analysed simulation time.

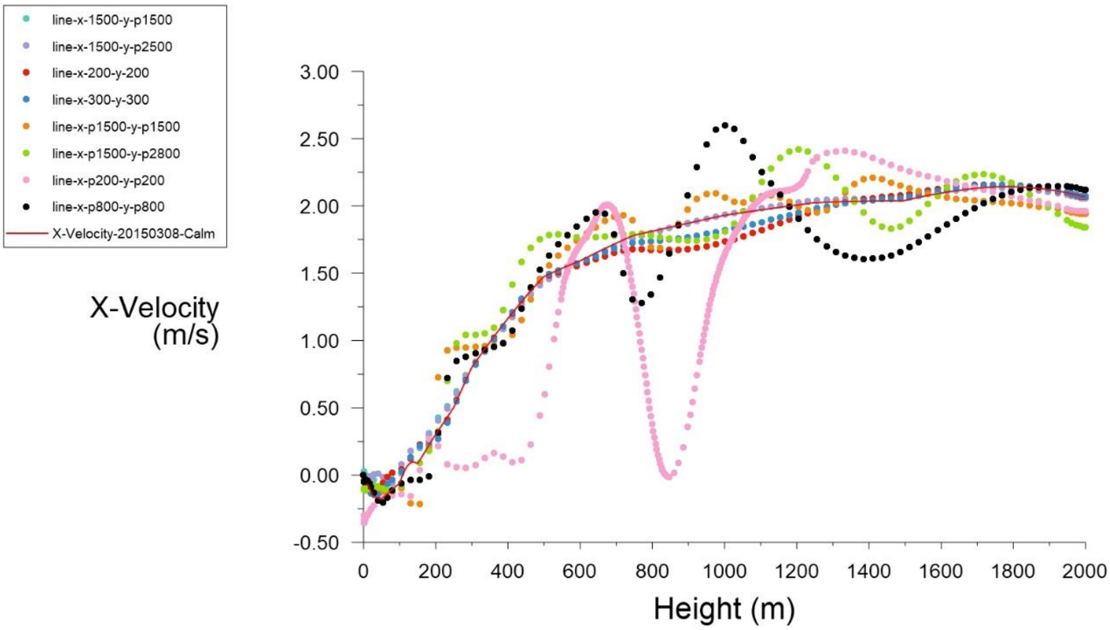


Figure 70. Velocity in the x-direction of the domain along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 68). Red line demonstrates the applied wind profile according to Figure 1 - 'Combiined' wind case at analysed simulation time.

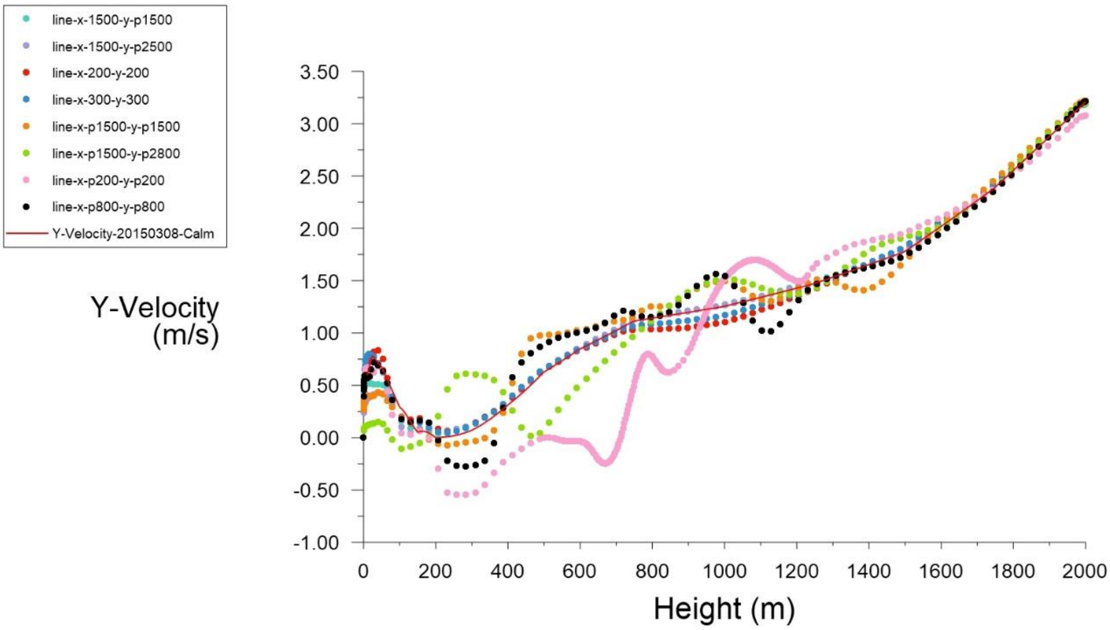


Figure 71. Velocity in the y-direction of the domain along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 68). Red line demonstrates the applied wind profile according to Figure 1 - 'Combiined' wind case at analysed simulation time.

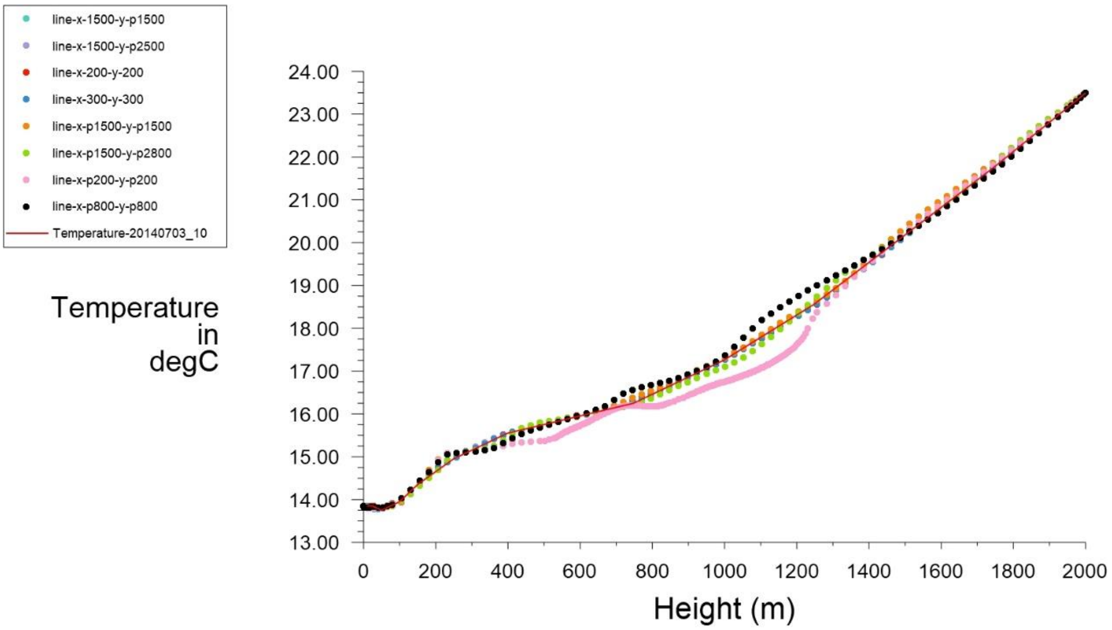


Figure 72. Temperature along a vertical sample line (from ground level to 2000 m) at different positions in the domain (see Figure 68). Red line demonstrates the applied wind profile according to Figure 1 - 'Combiined' wind case at analysed simulation time.

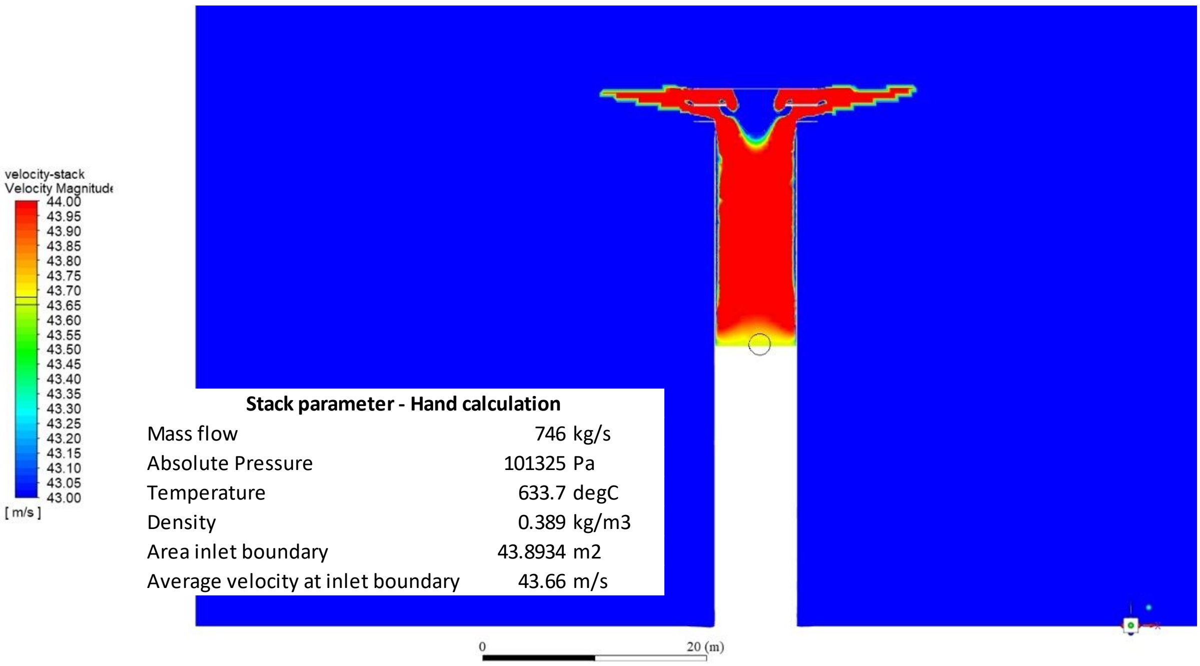


Figure 73. Contour plot of velocity magnitude through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map – 'Combined' wind case.

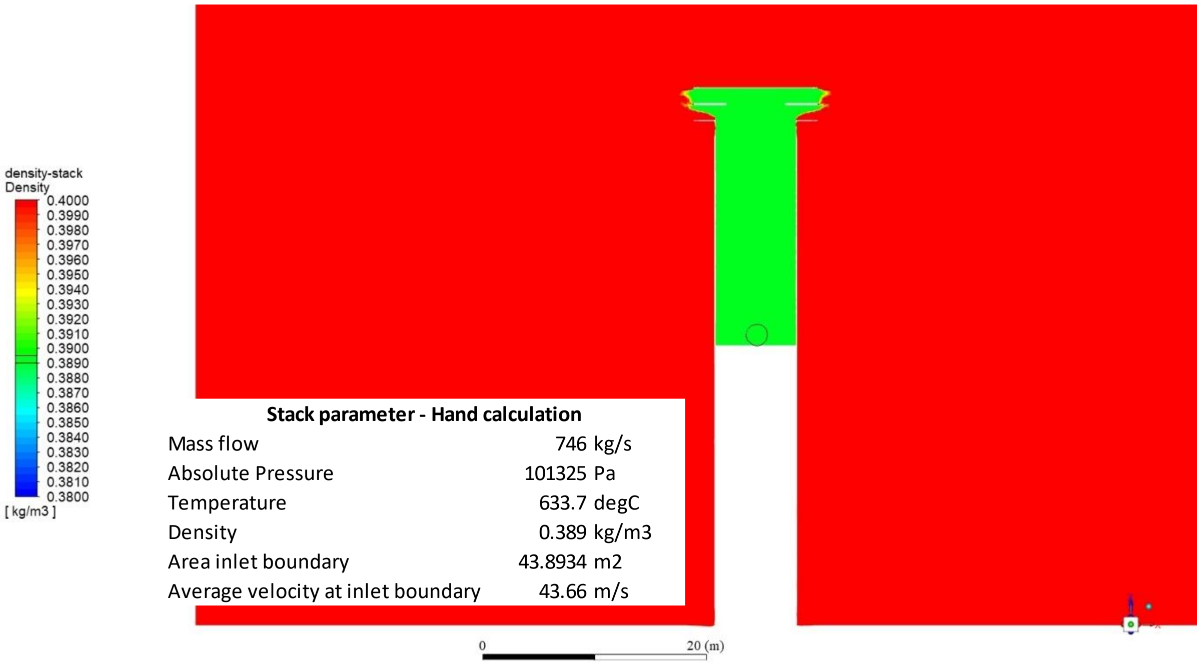


Figure 74. Contour plot of air density through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - 'Combined' wind case.

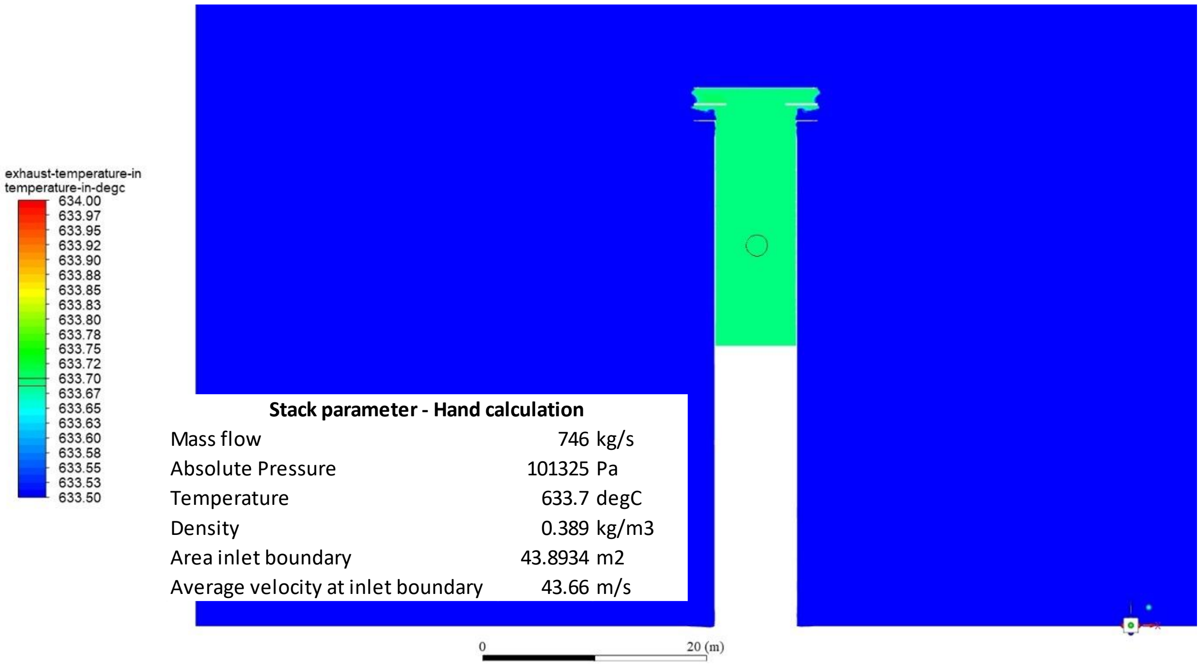


Figure 75. Contour plot of temperature in °C through the stack and PDD. The centre of the circle indicates the location of the probe highlighted in the colour map - 'Combined' wind case.

APPENDIX C

- CSV-File of velocity magnitude, u-, v-velocity and temperature along plume trajectory based on maximum plume velocity (*TPM03-GE-ModDesign-Case20140703_10-02-max-velocity-trajectory-20200528.csv*)

- CSV-File of vertical velocity and temperature along plume trajectory based on maximum vertical plume velocity (*TPM03-GE-ModDesign-Case20140703_10-02-max-vertical-velocity-trajectory-20200528.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 6 m/s. (*TPM03-GE-ModDesign-Case20140703_10-02-average-plume-velocity-and-area-6m-s-20200528.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 4 m/s. (*TPM03-GE-ModDesign-Case20140703_10-02-average-plume-velocity-and-area-4m-s-20200528.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 2 m/s. (*TPM03-GE-ModDesign-Case20140703_10-02-average-plume-velocity-and-area-2m-s-20200528.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 1 m/s. (*TPM03-GE-ModDesign-Case20140703_10-02-average-plume-velocity-and-area-1m-s-20200528.csv*).

- CSV-File of velocity magnitude, u-, v-velocity and temperature along plume trajectory based on maximum plume velocity (*TPM07-GE-ModDesign-Case20150308_Calm-01-max-velocity-trajectory-20210504.csv*)

- CSV-File of vertical velocity and temperature along plume trajectory based on maximum vertical plume velocity (*TPM07-GE-ModDesign-Case20150308_Calm-01-max-vertical-velocity-trajectory-20210504.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 6 m/s. (*TPM07-GE-ModDesign-Case20150308_Calm-01-average-plume-velocity-and-area-6m-s-20210527.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 4 m/s. (*TPM07-GE-ModDesign-Case20150308_Calm-01-average-plume-velocity-and-area-4m-s-20210527.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 2 m/s. (*TPM07-GE-ModDesign-Case20150308_Calm-01-average-plume-velocity-and-area-2m-s-20210527.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 1 m/s. (*TPM07-GE-ModDesign-Case20150308_Calm-01-average-plume-velocity-and-area-1m-s-20210527.csv*).

- CSV-File of velocity magnitude, u-, v-velocity and temperature along plume trajectory based on maximum plume velocity (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-990s-max-velocity-trajectory-20210517.csv*)

- CSV-File of vertical velocity and temperature along plume trajectory based on maximum vertical plume velocity (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-990s-max-vertical-velocity-trajectory-20210517.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 6 m/s. (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-990s-average-plume-velocity-and-area-6m-s-20210527.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 4 m/s. (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-990s-average-plume-velocity-and-area-4m-s-20210527.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 2 m/s. (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-990s-average-plume-velocity-and-area-2m-s-20210527.csv*).

- CSV-File of average vertical and absolute plume velocity as well as plume area. Plume area is defined as horizontal area in which the vertical plume velocity is > 1 m/s. (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-990s-average-plume-velocity-and-area-1m-s-20210527.csv*).

- Video of plume envelope where the absolute velocity is 8 m/s depending on the time for the 'combined' wind case. Colour of envelope refers to the height. (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-IsoSurfaceAbsVel8-V2-20210517.mov*)

- Video of plume envelope where the absolute velocity is 8 m/s depending on the time for the 'combined' wind case. Colour of envelope refers to the height. (*TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-IsoSurfaceAbsVel8-V2-20210517.mov*)

- Plume extent shown as a contour plots of vertical velocity in a horizontal plane at 198 m (650 ft) elevation (above MSL) for all three wind cases. Plume area is clipped to vertical plume velocity of >1, >2, >4, and >6 m/s. Grid spacing in plot is 20 m with stack centre at the origin (red lines).
    - 'Initial' wind case
        - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel1-650ft.jpg*
        - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel2-650ft.jpg*
        - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel4-650ft.jpg*
        - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel6-650ft.jpg*

- Calm wind case
  - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel1-650ft.jpg*
  - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel2-650ft.jpg*
  - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel4-650ft.jpg*
  - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel6-650ft.jpg*
- 'Combined' wind case
  - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel1-650ft.jpg*
  - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel2-650ft.jpg*
  - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel4-650ft.jpg*
  - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel6-650ft.jpg*

- Plume extent shown as a contour plots of vertical velocity in a horizontal plane at 213 m (700 ft) elevation (above MSL) for all three wind cases. Plume area is clipped to vertical plume velocity of >1, >2, >3, >4, >5, >6, >7, >8, >9, and >10 m/s. Grid spacing in plot is 20 m with stack centre at the origin (red lines).
  - 'Initial' wind case
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel1-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel2-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel3-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel4-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel5-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel6-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel7-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel8-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel9-700ft.jpg*
    - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel10-700ft.jpg*
  - Calm wind case
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel1-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel2-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel3-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel4-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel5-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel6-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel7-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel8-700ft.jpg*
    - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel9-700ft.jpg*

      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel10-700ft.jpg*
  - 'Combined' wind case
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel1-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel2-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel3-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel4-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel5-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel6-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel7-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel8-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel9-700ft.jpg*
      - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel10-700ft.jpg*

- Plume extent shown as a contour plots of vertical velocity in a horizontal plane at 305 m (1000 ft) elevation (above MSL) for all three wind cases. Plume area is clipped to vertical plume velocity of >1, >2, >3, >4, >5, >6, >7, >8, >9, and >10 m/s. Grid spacing in plot is 20 m with stack centre at the origin (red lines).
  - 'Initial' wind case
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel1-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel2-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel3-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel4-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel5-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel6-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel7-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel8-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel9-1000ft.jpg*
      - *TPM03-GE-ModDesign-Case20140703_10-02-plume-area-Zvel10-1000ft.jpg*
  - Calm wind case
      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel1-1000ft.jpg*
      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel2-1000ft.jpg*
      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel3-1000ft.jpg*
      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel4-1000ft.jpg*
      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel5-1000ft.jpg*
      - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel6-1000ft.jpg*

   - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel7-1000ft.jpg*
   - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel8-1000ft.jpg*
   - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel9-1000ft.jpg*
   - *TPM07-GE-ModDesign-Case20150308_Calm-01-plume-area-Zvel10-1000ft.jpg*
- ‘Combined’ wind case
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel1-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel2-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel3-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel4-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel5-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel6-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel7-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel8-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel9-1000ft.jpg*
   - *TPM07-GE-ModDesign-CaseW_20150308_Calm_T_20140703_10-01-plume-area-Zvel10-1000ft.jpg*