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Air pressure and wind velocity - modelling Ember Attack Within The Urban-Rural Interface.

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As population change places pressure on expanding regional and metropolitan urban boundaries, so the threat of bushfire at the rural/urban interface increases. This paper presents a range of 2D and 3D 1:40 and full scale modelling investigations. Various relationships are explored between the urban and rural interface with respect to: air pressure; changes in wind pattern; vectorial velocity; and the deposition of hot ash and firebrand deposits around single story building forms, both as standalone and within an orthogonal array and cul-de-sac relationships.

Keywords: Urban environmental risks (eg. bushfires), Peri-urban planning
1. INTRODUCTION

The urban/rural interface exists wherever structures, irrespective of habitation, are intermixed amongst trees and other combustible vegetation. The urban/rural Interface or peri-urban as referred to by Cottrell (2005) can be found throughout Australia at the urban fringe of cities and townships. The peri-urban landscape, by definition, is a transition zone where rural and urban land-uses, activities and social processes, overlap and are interspersed. A rudimentary view of the peri-urban, from a macro perspective, would be to draw a line that encompasses the municipalities that encircle the outer metropolitan area. From a micro perspective the peri-urban are often seen as green wedges which are associated with waterways with relatively high vegetation, open planes grass and cropping lands, parklands and state or national parks which meet the urban environment and establish the urban/rural Interface’.

Communities in the urban/rural interface, illustrated in Figures 1 and 2, feature relatively large populations living in close proximity to highly flammable bush land areas and are often complicated by rugged topography and stony rises with poor access. As suggested by (Miler, Carter and Stephens 2002) “A high proportion of the inhabitants in these areas are commuters with little experience of living in the bush or fending for themselves in a major fire”.

Due to the nature of bushfires, houses in rural areas have a higher risk of damage or destruction than those in urban regions. The extent to which a bushfire will penetrate the urban-rural interface therefore depends on the locality of houses to the urban/rural interface. Fires burning within trees generate more air-borne embers than those in grassland. As a result the embers travel further and burn longer and pose a greater threat (Wilson 1984).

There have been many studies into the transportation/life cycle of burning debris, hence the natural progression is to further understand the potential for these particles forming on or adjacent to a building. Ash and ignited debris within this paper will be restricted to particles ranging from 0.5mm through to 25mm. Limiting these particles to a particular field facilitates the application of a mathematical model to calculate the potential transportation of debris. This does not dismiss the issues related to the transportation of larger items but merely investigates the deposition of small ignitable debris that could be caught up or deposited around potentially combustible building surfaces. Each wildfire is unique, therefore only an indicative distribution model is suggested in this paper. The studies undertaken suggest that the placement and distribution of building forms appear to fall within a range of distances and orientations, which, with further research, may possibly be of assistance to urban planners when predicting risk within the interface.

The formulae utilised in both the wind tunnel and fluid mapping studies is listed in appendix 1. In addition, the paper explores the application of the CSIRO’s ‘Vertical Wind Tunnel’ and the findings by (Wang 2003/06). The equations were discussed and evaluated by (Wang 2003/06), in the paper ‘Ember Attack: Its role in the
destruction of Houses during ACT Bushfires in 2003. The first equation relates to the effects of a flame/fire plume on the up lofting of firebrand materials, the second considers the size of firebrand materials and the potential and distance for such material to travel downwind (see appendix 2) NB Both equations can be applied in the following Figure 3, as presented by (Wang 2003/06)

Figure 3. – Illustrating the trajectory of firebrand materials within a presented air stream (Wang 2003/06)

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2 MONOPITCH

Rollo, Luther, Atkinson, 1999, and Rollo and Honey, 2003, correlated the relationship between wind speed and building form with the transportation characteristics of various sizes of fire brand material developed by Cheney and Sullivan 1997. Given the variables of wind direction, wind speed, and topography, their research assessed the behaviour of a single story mono-pitch base model on an unobstructed horizontal ground plane subjected to a scaled 7m vertical wind profile ranging between 28-35 KM/hr.

The work compared the results of two different testing procedures, fluid mapping and wind tunnel studies - both of which established a close correlation and therefore provided valuable visual as well as measurable data. The purpose of this paper is to elaborate on the findings of this earlier research and to introduce the spatial modelling and testing undertaken by Honey 2003 and Honey 2008. The diagram below illustrates the effect of time on the ignition and potential transportation of firebrand materials.

Figure 4 - Propagation and Transportation of Firebrand Material (S.Honey 2008).

With the application of both fluid mapping and wind tunnel testing the investigation assessed the cross-section characteristics of a 1:40 scaled 25sqm base model on a level field, presenting a cross-sectional profile of
width 5.0m x length 5.0m x a height ranging from 2.4 to 4m, with no re-entrant corners. Restricting the analysis to four permutations with respect to orientation and placement on a horizontal ground plane, the investigation assessed the response of the base model when positioned within a range of scaled wind speeds.

Tests were first conducted on the fluid mapping table (1m x 0.78m) with the use of a series of black Perspex models constructed at a scale of 1:40. Although this method only provided a two dimensional representation, and could only offer a maximum scaled wind speed of 2Km/hr, it nonetheless facilitated a quick appraisal of each of the scenarios under investigation and provided an informed sense of direction for proceeding with the Wind Tunnel tests. With each of the four scenarios - M1G, M1E, M2G and M2E – a grid comprising 30 separate wind speed measurements were recorded and correlated against the windfield transportation characteristics for ash, ember and firebrands compiled by Cheney and Sullivan, 1997, (See Figure 5). The results of the correlation of the two separate sets of data are illustrated in the Ash & Ember Transportation & Fallout Section Profiles figures 6.1-6.4.

<table>
<thead>
<tr>
<th>Wind speed km/hr</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>Rate of fire spread is equivalent to backing rate of spread, (ie without the aid of wind)</td>
</tr>
<tr>
<td>5</td>
<td>Threshold wind speed (the wind speed at which a fire moves continuously forward as a heading fire)</td>
</tr>
<tr>
<td>10+</td>
<td>Fine ash particles become transported within the wind field</td>
</tr>
<tr>
<td>20-25+</td>
<td>Fire brands and embers are blown along the ground and start to become transported within the wind field (ie any burning material originating from one fire which can start another, eg: commonly bark, but also leaves, seed heads and sparks etc)</td>
</tr>
<tr>
<td>37</td>
<td>Average wind speed recorded at Essendon Airport, Melbourne, on Ash Wednesday, 16 February 1983. Gusts ranged between 18km/hr and 81km/hr (NB While hot strong northerly winds increased to average mean speeds of 45-50 km/hr throughout the day, a frontal change reaching Ceduna at 1230hrs, Adelaide at 1445 hrs and Melbourne at 2030 hrs brought wind speeds in excess of 70km/hr with gusts up to 110 km/hr.)</td>
</tr>
</tbody>
</table>

Figure 5 Wind field transportation characteristics for ash & firebrands debris, Cheney and Sullivan, 1997.
As the wind profile moves over the base model three areas of low pressure develop: 1) The base of the structure on the windward side - with a drop in wind speed from 28Km/hr at 12 meters in front of the model, to 9-10Km/hr at the face of the structure; 2) The leeward slope of the mono-pitch behind the apex, 8Km/hr down to 4Km/hr; 3) The rear wall and base of the structure on the leeward side, 8-10Km/hr.

These conditions appear to facilitate the collection of debris: 1) on the ground and at the base of the model on both the windward and leeward sides; 2) on the leeward slope of the mono-pitch, where it appears to slide back down the face of the leeward wall.

As the wind profile moves over the base model two regions of note arise: 1) The base of the structure on the windward side, with a drop in velocity from 30Km/hr at 12m in front of the form, to 8Km/hr at the face of the structure; 2) Behind the apex of the mono-pitch, the pressure drops from 32Km/hr to 14 and 9Km/hr and then falls away rapidly to 2Km/hr at the base of the leeward wall.

Similar to M1G these conditions appear to facilitate the collection of debris on the ground and at the base of the base model on both the windward and leeward sides with significant deposits being forced back onto the rear leeward wall as the airflow over the apex of the mono-pitch becomes turbulent. Any openings into the base model at this level seem to permit the entry of debris from the leeward side.
With the apex of the mono-pitch oriented windward and an uninterrupted elevated space of 0.6m beneath the base model, the wind profile is significantly altered as the structure begins to adopt the characteristics of an aerofoil. Three low pressure zones once again arise: 1) The first occurs on the windward side, within 1-2m off the face of the model. This appears to generate a high pressure zone at ground level near the base of the structure as the wind passes beneath to leeward; 2) As with M1G, the second drop in pressure occurs on the slope of the mono-pitch, falling from 28km/hr down to 6Km/hr; 3) The third region takes place on the leeward side of the model. However, while the velocity drops from 10 to 7Km/hr near the face of the rear wall, it also rises steeply to 26Km/hr between the base of the structure and ground level. This creates a high pressure band extending 2m out from the bottom leeward edge of the model generated by the accelerated air flow passing beneath.

Altering the wind field to generate a high pressure zone beneath the base model appears to shift the windward and leeward debris collection points away from the base of the structure. While the mono-pitch will facilitate a primary collection point, it would appear that a significant proportion of the debris striking and falling out down the face of the leeward wall would be re-transported 3-4m away from the rear of the model. On the other hand, orienting the apex of the mono-pitch windward presents the larger of the two vertical faces to the wind-field. This appears to impact significantly on the approaching wind velocities. Hence critical fallout points would begin at 12m to the front of the model and rise to 3-4m above ground level within 8m of the structure. This may promote significant capture of debris before the structure which could affect air velocities beneath the base model.
Orientating the mono-pitch windward eliminates the three primary debris collection points. The high wind velocities recorded passing beneath the structure are still maintained, and presenting the shorter of the two vertical faces to the front improves the overall aerodynamics of the base model by minimising the impact on the transportation characteristics of the advancing wind field. The critical fallout points begin to arise at 8m in front of the model and only reach a height of 2.5m at 4m from the structure. This reduces the level of debris capture before the base model and increases the likelihood of maintaining high wind velocities beneath the model through to the leeward side of the structure. NB a 25sqm base model is incommensurate with the sectional profile presented by the typical 200+ sqm detached suburban house, which often presents a plan dimension of 10+m x 20+m.

3 MONOPITCH ARCHICAD MODEL - PLAN ORIENTATION 45 DEGREES TO AIR FLOW

Honey 2003 carried out further 3-dimensional Wind Tunnel studies of the solid 1:40 scale model of the mono-pitch base model utilising five points of plan orientation, 0, 39, 45, 90, 180, with 0 being perpendicular to the airflow. Each model is described within a 3D lattice comprising 132 points surrounding the structure (as distinct from the 18-30 utilised in the 2 dimensional analysis). These range from 11m before and 7 meters behind the structure and from 0.8m-7.0m above ground level. The results map a three-dimensional representation of the critical wind speed thresholds, presented by Cheney and Sullivan (1997), within Archicad, version 7 (ie less than 10Km/hr, 10-20 Km/hr and 20-25 Km/hr). Honey’s spatial models essentially represent parametric surfaces of change in air pressure, indicating indicative fallout points of ash, ember and fire-brand debris. Figures 8a, 8b, 8c, and 8d present the mono-pitch building form oriented 45 degrees to the airflow. In this example, the site is not level, as was the case with the 2D profiles, but resembles cut and fill on a 1:5 inclined ground plane. The model indicates turbulent conditions at the leading corners of the building, and accelerated wind speeds along the side walls of the structure. The pronounced points of turbulence at the corners would appear to interfere with the transportation characteristics of embers approaching to the left and right of the centre axis of the wind field and hence appear to promote the fallout and collection of fire-brand debris within a low pressure zone near the base of the side walls.
4. ESTABLISHING A PILOT STUDY FIELD ARRAY

Establishing a field-testing array involved the positioning of two shipping containers. In order to evaluate the local wind patterns over a four week period, one container was oriented in an east-west longitudinal axis with the longest face orientated towards the north and south and the second in a north-western/south-eastern longitude axis. After this initial test period both containers were oriented on a north-western/south-eastern longitude axis in order to take advantage of the South-easterly/North-westerly changes. To monitor all results a grid was established based on the array utilised in the wind tunnel tests with a horizontal dimension line pegged out at intervals of 2, 4, 6, 8, 10, 15, 20 and 30m, to the north and south of the structures (See Figure 9a and 9b). A further six horizontal dimension lines were established on the sides of the containers. These divisions were orientated longitudinally on a north-south axis. Vertical test points of 0.6, 1.2, 1.8, 2.4 and 3.0m correlate to the points at which the north-south and east-west dimension lines intersect. Wind speeds were measured using a tripod with a domestic standard “Heavyweather” WS-2300 series Wireless Weather Stations (433MHz) and the Silva ADC Summit hand-held wind speed monitor. Both devices were used concurrently, to validate the recorded results.

Introducing cultivated dry clay dust into the prevailing wind presents a visual account of the air flow as it moves around the shipping container elevated 600mm off ground (see Figures 10a, 10b and 10c).
The results of the first phase of impact recorded to the windward side of the structure, show areas of increased compression. Recorded data indicated that the form influenced the airflows at grid interval -6, or 6 metres to the windward side. This is illustrated in Figure 10a. Where these compression forces were visually and electronically recorded, a corresponding average increase in airflow from 14m/s to 19m/s was observed at between -20 to -15m and – 4 and 0 respectively.

As the presented airflow proceeded over the form, areas of reduced compression and transportation were recorded to the leeward side. The second phase recorded an area of increased turbulence, compression and airflow to the underside of the form, with an average recorded wind speed of 22m/s.

Further recorded data illustrated a constant airflow present to the underside of the form averaging 19m/s at -2m, and 24m/s at +2m. On average, this increase in recorded airspeed was in the order of 5m/s (or 20% increase). This may suggest that the frictional forces of the air being compressed under the form are reduced, due to the less obstructive inclined orientation of the windward wall envelope presented to the airflow.

The third phase of observations recorded that between 0.8m and 2.4m vertically from natural ground level to the leeward side, areas of low airflow were recorded progressing 0m out to –10m from the face of the container. This highlights a large area of reduced air pressure and an increase in the deposition of debris.

5. BASE MODEL - WITH ADJACENT SECONDARY OBJECTS

Drawing on Wang’s research (2003/2006) further fluid mapping studies were developed to attempt to model the effects of asymmetric objects, such as landscape features and outdoor installations, in close proximity to the 5x5m scaled base model. A fire front often presents multiple ignition points and therefore a strategic approach to the proximity and type of landscape and vegetation would seem to play a role in the accumulation and eventual transportation of fire brand material. NB The height of the objects could not be modelled in the 2 dimensional fluid mapping study.

The study indicates that the proximity between intermediate objects, as seen in Figure 11a, and a base model, appears to impact on turbulence and wind speed, and therefore influences the transportation of ember material. Importantly, in Figure 11a, the objects, represented by the cluster of three multi-faceted asymmetric forms, appears to indicate that as the flow of the dye is redirected turbulence is increased. Once past the objects the flow disperses. This causes a shadow effect behind the secondary forms, which could be conducive to the deposition of ember material and hence the propagation of smaller spot fires. In Figure 11b the objects have been relocated to the windward side of the base model which now bears the full impact of the dye flow - illustrated by the compression of the dyelines and the resultant increase in dye intensity. It was also noted that in this case, the location of the objects appeared to concentrate the airflow to the rear or leeward side of the structure in a funnel like effect, increasing the potential for embers to fall out of the airflow and collect on the leeward side of the base model.
6. MULTIPLE BASE MODELS – SINGLE ROW

The examples seen in (Figures 12a and 12b) represent multiple base models resting on ground spaced at 2m intervals and oriented perpendicular to the simulated wind conditions. The first area to register a drop in wind speed takes place within 2m of the windward walls. As the dye flow lines are compressed and dispersed around the corners of the base model forms, the dye trace clearly indicates an increase in velocity. The second point where a marked change occurred is registered on the leeward side of the row of base models (see Figure 12b). Higher wind speeds appear to be deflected between the forms, which appear to produce a fall in pressure on the leeward side of the structures. Significant backwash or vacuum pressures seem to be present; this is referenced towards the rear of the structure (represented by the blue shading) for at least five meters along the ground plane. NB the conditions present between two adjoining structures with multiple forms were also considered in relation to inter-property fencing and or physical connectivity. As indicated by Raphaele Blanchi and Justin Leonard (April 2005), fences were a contributing factor in flames climbing up between houses, where the fence was constructed of combustible materials.

7. MULTIPLE BASE MODELS – MULTIPLE ROWS – (Proposing the Ember Channel)

Further studies into fire events throughout South-eastern Australia highlight the importance of effective planning guidelines in the position of multiple built forms at the interface, where factors of proximity and building density appear to directly affect the scale and shape of wind turbulence and negative pressure zones. Orientation to the potential fire risk and the proximity of neighbouring structures form the basis for the next stage of the study (See Figures 13a and 13b)

Fluid mapping was undertaken to try and understand the impact on the second row of base models from the bushland interface. Similar to the study of ‘multiple base models - single row’, the dye penetrates the first row and, as seen in Figure 13a creates a series of shadows or negative pressure zones to the leeward side of the base models. However unlike the previous study, the presence of a second row of base models, set 30 metres behind the first and separated by a 10m interval between adjacent base models, appears to consolidate or channel the wind by the time it encounters the third row of base models (see figure 13b). Further investigation of this observation may provide a means of sculpting the landscape in advance of the first row of base models at the rural interface, in a way which might help to manage the transportation of embers between the rows of base models and channel them in a way which could possibly mitigate their
deposition. It would appear that this frustration of the wind flow caused by the build up of a complex array of intermittent low pressure zones has two effects on the condition of these wind channels. First, the cross section area of the accelerated ember channels (EC) is significantly reduced, which in turn may make them less predictable and hence more susceptible to micro changes within the structure of the cluster presented by multiple rows of base models. As figure 13b appears to indicate, it is the length of the negative pressure zone that seems significant. While the shadow continues and partially envelops the base model directly opposite, it was found that the shadow in the lower two base models in the second row did not continue. The turbulence that occurred was not isolated to the lower portion of the test, and was directly dependent on the angle to the prevailing wind conditions of the first row of base models. As these series of tests were designed for ideal perpendicular conditions, it is important to note that base models in the field are subjected to an array of different variables, such as different wind directions, topography, and vegetation which cannot be effectively tested in a two dimensional environment.

8. MULTIPLE BASE MODELS – MULTIPLE ROWS – 45° ORIENTATION

Orientation within the landscape is one of the fundamental design considerations that statutory town planners address when considering the future layout of a suburb, neighbourhood, street and ultimately individual allotments. Within the interface the orientation of a structure is an important consideration. It is a requirement of the Wildfire Management Overlay- Application Kit, published by the CFA, and enforced by local municipalities in order to consider the exposures inherent to each particular site. These studies and the 1:1 scale analysis, attempts to understand more the effect of orientation with respect to the direction of wind and the resultant vectorised air flows that occur over a given array of base models.

Proximity, as indicated in the previous studies, seems to affect wind flow between adjacent structures. Likewise, Figures 14a and 14b indicate that orientation with respect to the prevailing conditions also plays a significant role. While a 45° plan rotation may assist in improving the aerodynamic performance of an isolated base model, Figure 14a would seem to indicate that an orthogonal array of base models encountering a 45° wind flow (similar to a south-westerly wind change encountering an urban fringe development oriented on a north-south axis) could well exacerbate turbulence conditions as the wind flow penetrates past the first row of base models. Compression and an increase in velocity would appear to occur at the leading corners of the first row of base models, but thereafter flows would seem to be subject to increased turbulence, which would translate into eddies and vortices and hence limit overall transportation rates.

The second Figure 14b is a relationship diagram where the exposures illustration from the Country Fire Authorities, Wild Fire Management Overlay Applicant’s Kit, has been applied to illustrate the frontal impact that could occur in a wildfire situation. The north points on each template show the south-westerly oriented dye trace. NB these conditions in south-eastern Australia are often indicative of a Total Fire Ban Day.

9 MULTIPLE FORMS – CUL-DE SAC CLUSTER – PERPENDICULAR AND AXIAL ORIENTATION

The final study undertaken examined the impact of cul-de-sac relationships, where the orientation to the prevailing wind is both aligned with the street (axial) and rotated 90° (Perpendicular). Studies undertaken by Bartlett (2004) analysed the average buffer distances from the fire front, the width of the buffer and the
number of houses destroyed during the Canberra Fires of January 2003. It was suggested by Bartlett (2004) that the average buffer widths were between 55m and 88m with the number of base models destroyed ranging between 16 and 56.

Bartlett (2004) indicated that the setback distances between the plantation and the suburbs of Duffy and Holder were sufficient to prevent direct flame contact from the front, but insufficient to prevent ember attack impacting a number of streets into the interface. This ultimately led to the destruction of many residences. While the fluid mapping study in Figure 15a illustrates the impact of a 90° orientation, to the cul-de-sac, Figure 15b depicts the same external conditions, but with the cul-de-sac axially aligned with the prevailing wind. The Figures indicate significant low pressure areas that directly impact on the adjacent base models.

In Figures 15a and 15b nine base models were tested where the street easement, setbacks and distances between representative structures were all scaled and the boundary fences and secondary objects removed (NB the setback from the centre of the road is 15 meters with the distance between base model ranging from 5.0m> to <7.5m). In Figure 15a where the street runs perpendicular to the flow and base models have been rotated at varying angles relative to each other, we find that the effects of turbulence to the windward side of the first row of base models echoes the dye trace pattern in Figures 14a and 14b. Furthermore, all of the base models, with the exception of the two at the top end of the cul-de-sac, present areas of negative pressure ranging from 0>5.0m. When studying the cul-de-sac rotated through 90 degrees (On axis with the wind flow), the results appear to indicate that small changes in the alignment, orientation and proximity of adjacent base models established a sequence of wind flow patterns which were more complex than those presented in the simple orthogonal arrays.

10. CONCLUSIONS & FURTHER RESEARCH

Smalley (p. 5, 2003) writes that “the growth of communities into previously forested areas is one of the three major factors that will propagate the pressures of the interface on communities. The other two are unusually severe weather events … and inadequate infrastructure due to the rapidity of growth or aging”. In summary, the effects of form, site and orientation, and proximity to other natural and artificial shapes within the landscape, all seem to play a significant role in the deposition of debris on and around a structure within the interface. As the studies suggest, a simple isolated 25sqm base model on a level field, presenting a cross-sectional profile of W5.0m x L5.0m x H2.4 to 4m, with no re-entrant corners, elevated uninterrupted by 600mm, and plan orientated 45 degrees to the wind, seems to perform better than when oriented on ground and perpendicular to the wind. NB once again, a 25sqm base model is incommensurate with the sectional profile presented by the typical 200+ sqm detached suburban house, which often presents a plan dimension of 10+m x 20+m.

In an attempt to simulate an interface neighbourhood by studying an arrangement of nine base models, with varying degrees of proximity and orientation, the conditions become much more complex than a single isolated base model. While a simple orthogonal array oriented to the prevailing wind seems to promote a more favourable set of conditions, a shift in wind direction can transform that array into a worst case scenario.
Probably the most interesting array under consideration, but yet to be studied, is a staggered arrangement of base models. In this scenario, it is anticipated that a check- aboard array, oriented on a north-south east-west axis may also be able to address a north-west or south-west wind change. The implications of this arrangement present a land-use pattern which sits somewhere in between the "Rural-Residential" and "Residential" planning typologies, which the authors have termed the "Interface Residential" zone. It inhibits the location of boundary fencing between allotments, advocates half the density which is currently being developed in new growth areas and suggests limiting subdivisions to double sized blocks, with coordinated building footprints and landscape plans to promote a staged implementation of houses across the interface zone. In time one would expect that the interface zone could eventually be re-classified into a residential zone, facilitating increased housing density within a more regulated framework, as the urban growth boundary moves further afield.

While the studies presented in this paper are not conclusive, and at best can only be considered to be indicative, they have nonetheless yielded an array of interesting and at times surprising set of results. Probably the most important conclusion to be drawn is that there appears to be a strong correlation between building form, wind speed, air pressure, and the deposition of ember material. Hence the interplay of these factors are worthy of further investigation so that planners and designers working on the interface have a more informed understanding the dynamics of wind when shaping landscape and building form within a peri-urban neighbourhood.

REFERENCES

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APPENDIX 1

7 SPECIFICATIONS

Fan: Richardson 'Buffalo' 445cp
1.1 Kw Max: 415V 2.4A
1410 RPM Fan Speed - 730 RPM

1.2m Sq x 2.0m long Tunnel

Formula used for calculating Full scale velocity in the wind tunnel: \( v = v_m \cdot m^3 \)

\( v_f \) = Full scale Velocity

\( v_m \) = Model Velocity

\( m \) = Model ratio

NB: When relating the four scenarios with the wind speeds recorded in the wind tunnel there appears to be a close correlation with the dye traces documented on the mapping table. This implies that while the two methods of testing reflect different types of flow (when the calculation of Reynolds's number is taken into consideration), with fluid mapping depicting laminar flow and the wind tunnel indicating either transitional or turbulent flow, the mapping table is nonetheless indicative of the conditions identified in the tunnel.

APPENDIX 2

\[ \frac{u - v_f}{u - 0.1u_f} = \frac{d}{d + h_p \tan \alpha}, \text{ i.e. } h_p = \frac{d}{u - 0.1u_f - (u - v_f) \tan \alpha} \]

Ellis (2000) – Effects of Fire/Flame Plume on the uplofting of firebrand materials (Wang 006)

\[ x_{min} = d + h_{p, min} \tan \alpha + \left( h_j + h_{p, min} \right) \frac{u_v}{v_i} \text{ and } t_{min} = \frac{h_p, min}{u_v, min} \frac{h_j + h_{p, min}}{v_i} \]

Clements (1977) – Transportation of Fire Brand Materials Downwind. (Wang 066)