16th Australasian Wind Engineering Society Workshop
Brisbane, Australia
18-19 July, 2013

Natural Ventilation in Hot Arid Environments

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Abstract

Natural ventilation in extreme environments is often ignored during the design phase due to the hot or cold climate. The reliance has therefore shifted to mechanical systems which require extensive amounts of energy to facilitate the associated internal volumes of the building. With the continual fast paced development of projects in areas such as the Middle East, regulations are being placed on the amount of energy available to each specific site. Although natural ventilation may not be practical in a residential or commercial office space for the majority of the year in these areas, there is scope to employ natural or mixed mode ventilation in other applications such as car parks and industrial facilities.

In this work, a case study for the natural ventilation of a warehouse facility located in the Middle East is presented and analysed. Wind tunnel testing in conjunction with numerical analyse has been undertaken to determine the internal comfort conditions for the facility for both thermal comfort and air quality. Additional analysis has also been carried out to ascertain the effects of optimising opening locations on the internal conditions as well as utilising a mixed mode mechanical-natural ventilation system.

Introduction

Wind-driven natural ventilation is typically designed into developments located in mild climates where the primary purpose is to provide sufficient air quality through circulation of the internal volumes of a building. Development of a natural or mixed mode ventilation system has also led to the reduction in the reliance on ventilation from mechanical systems and in turn energy consumptions from these systems.

The limitation in energy supply available for development sites has led to the search for alternative means of reducing energy consumption of a building, including mechanical systems. Areas of developments which are generally deemed to be less sensitive and critical to be mechanically ventilated include carpark and warehouse facilities. Ventilation for these aspects can typically be provided through means of opening locations in different pressure fields to provide cross-ventilation. However the ability to achieve adequate amenity from hot or cold climates requires additional analysis to ensure that thermal conditions do not exceed tolerable safe levels.

Natural ventilation in extreme climates does not come without its limitations. Facilities located in hot climates are required to maintain adequate amenity for its users (workers, occupants, patrons etc) to ensure that thermal heat stress is not induced.

This paper presents a combined analysis utilising wind tunnel testing and numerical modelling techniques to model and determine the thermal comfort levels within a warehouse facility. This paper outlines details of the methodology and applicable comfort criteria for occupants working in an industrial facility located in a hot dry climate.

The local climate has a significant impact on the optimal design of a building structure. This includes the location of external openings, construction materials used and the internal partitions and layout and extent of the internal heat sources. Through the investigation of the presented case study, the effects of internal heat sources and proposed opening locations for traditional warehouse factory layouts are investigated. Through a review of the results of the base case and mapping of the mean pressure coefficients across the exterior of the building, a clearer understanding of suitable opening locations can be formulated to achieve greater amenity in terms of thermal comfort for the occupants.

Thermal Comfort Standards

Numerous standards have been published with guidance on the assessment of the effects of thermal environments on human comfort. These standards are broken into three key areas; cold, moderate and hot environments. The requirements for thermal comfort for moderate climates are widely documented including ANSI/ASHRAE 55-2010 and ISO 7730. These standards are limited as to the mean temperature range which they consider and hence acclimatisation of the individuals concerned. ISO7243 provides some guidance for hot climates up to a limit of 33°C, while ISO 7933 provides provisions for temperatures which exceed this. Parsons (2006) detailed that an acclimatised fully clothed worker is able to function effectively provided their deep body temperature does not exceed 38°C.

As thermal comfort is dependent on numerous factors including but not limited to; the relative humidity, temperature, metabolic rate of the individual and clothing, what is deemed to be acceptable varies depending on the type of climate. For comfort of persons located in hot and dry environments, research has been carried out by Marincic et.al. (2009) as well as Akande and Adebamowo (2010). Their research has looked at the thermal comfort level for persons located in dry climates with a mean temperature in excess of 40°C, similar to that experienced throughout the Middle-East. These studies utilised the sensation voting system similar to that detailed in ASHRAE 55, and found that general people are comfortable with an indoor temperature of 32°C, however are willing to experience temperatures up to 35-36°C. Higher temperatures may also be tolerable provided that there is sufficient airflow experienced by the worker. This is due to the cooling sensation created by the interaction between perspiration and the airflow passing over a person's skin.

From consideration of the design guidelines presented through ISO7933 and field studies carried out in Nigeria and Mexico, warehouse facilities are able to provide comfortable working conditions through the use of natural ventilation for temperature ranges up to 40°C with experienced airflows of 1m/s.

Methodology

The design of a hybrid natural and forced ventilation design of a factory warehouse located in a hot dry climate can be achieved through combined analysis from wind tunnel and numerical modelling for the project. The thermal comfort for a development located within a hot climate is largely dependent on the local climate. Furthermore materials used for the construction of the development, as well as the use of the internal space, including associated machinery (heat source) needs to be accounted for to develop the working conditions which can be expected.

The method detailed in this paper is outlined as follows:

- Detailed climate analysis for the site location
- A scale model of the subject development used as part of a detailed wind tunnel study
- 3D modelling of the subject development, including the internal layout and proposed machinery and production facilities.
- Computational Fluid Dynamics(CFD) modelling of internal conditions utilising local climate analysis and results from the wind tunnel study as inputs for the Boundary Conditions.
- Determination of the expected air quality and internal velocities.
- Optimisation of the internal conditions of the subject development.

Local Climate

The internal conditions any development is highly dependent on the local climate where the site is located. This varies both throughout the year and also over a 24hr period. The climate for the site location therefore needs to be analysed for the entire year for during both day and night time scenarios. From this analysis, trends can be identified for the design temperatures, humidity and wind conditions (directionality, frequency and velocity) that need to be accounted for, as detailed in "Figure 1". By understanding the climatic conditions for which the development is exposed to, a design development strategy can be formulated to account for and capture the most favourable effects, such as prevailing breezes.

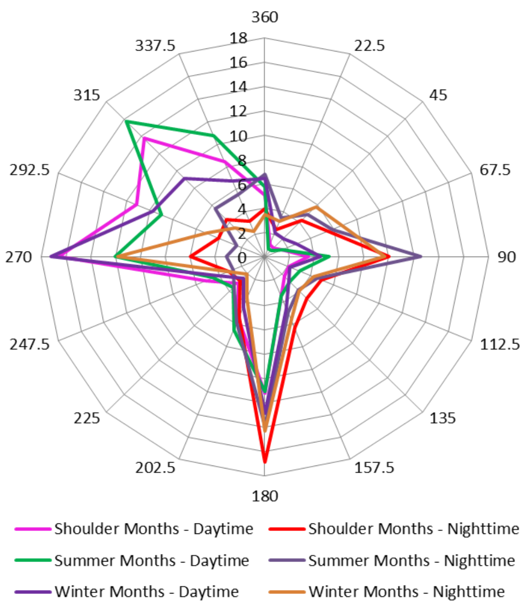

Figure 1. Percentage of Observations of Wind Directions For Day and Night and For Different Seasons.

Scaled Wind Tunnel Model

As part of the wind tunnel study a detailed scale model of the development and local proximity buildings is required to enable accurate measurement of the net pressures which will be experienced over the surface of the building development. This includes the net pressures exerted at the various opening locations proposed, this can include windows and doors; roof ventilators and skylights; stacks; and specially designed inlet or outlet openings.

Natural ventilation through the building is driven by the pressure differential created across the opening generated by the ambient pressure and temperature differences. Intentional flow of outdoor air due to wind and thermal pressures through controllable openings can effectively control contaminants (air quality) and temperature of a volume. The ability for temperature control for the internal space is highly dependent on the local climate that the development is located, with mild climate regions able to provide greater percentage of acceptable thermal conditions.

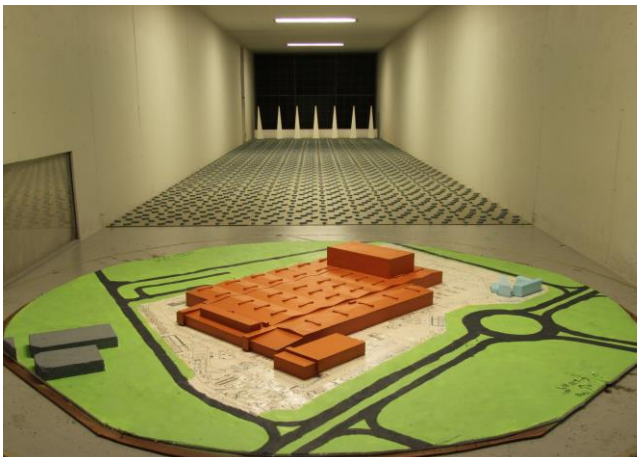

Figure 2. Model in Windtech's No2 Boundary Layer Wind Tunnel

Utilising wind tunnel testing to determine the external pressures experienced at the various opening locations as boundary conditions for the CFD model enables far greater accuracy for the net pressure inputs. Wind tunnel testing accurately accounts for the turbulent boundary layer wind profile which the subject development would experience. Furthermore, wind tunnel testing enables a faster turn-around and feedback to the client to minimise hold ups in the project's design process.

The air quality and thermal conditions that the occupants of the development are subjected to must be focused on the expected daily occurrence. While extreme conditions for both wind and temperature do occur, we must consider the conditions the occupants will considered for the vast majority of the time. Also not that natural ventilation of the internal volume will only be enhanced with increased external wind conditions, helping to drive and improve the air quality and internal temperatures of the facility.

Computational Model of the Internal Volume

The computer model of the internal areas of the facility is used to account for the internal layout of the development facility as well as the various internal heat sources. The thermal properties of the building envelope were also modelled. This is important in developments located in extreme climates or developments with significant heating or cooling sources located inside. The internal layout of the facility, including location of internal walls between external openings will largely affect the internal flow, especially for large facilities.

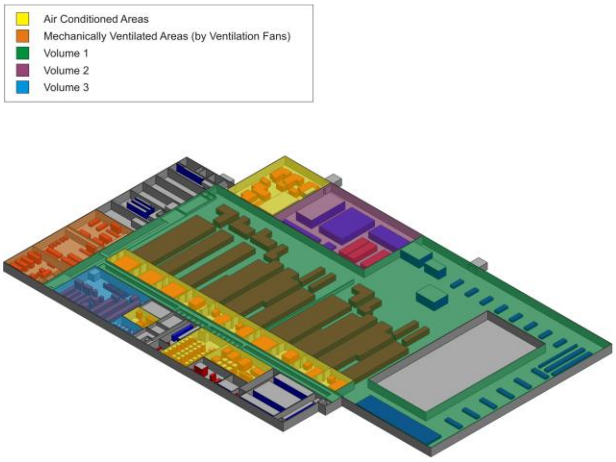

Figure 3. Computer Model of the Internal Layout of the Facility

Insulation of roof and the walls of the development can affect the heat transfer for the external environment due to both the sun's radiant heat and transfer of heat loads between internal volumes can significantly affect the internal conditions experienced by the occupants. As the local climate varies throughout the day and year, the variance in the radiant temperature generated by the sun on the development needs to also be account for. This could highlight the possibility for night-time cooling (heat flushing).

The heat output loads/temperatures of the various machinery and sources need to be accurately accounted. This includes the density of occupants of the facility and any moveable machinery such as forklifts.

CFD Model Analysis

For this case study, a CFD model of the subject development was carried out using ANSYS software employing the standard κ-ε turbulence model. The computation mesh consists of 1,194,323 cells for Volume 1, 155,164 for Volume 2 and 119,617 for Volume 3.

This CFD model was used to model the effect of temperature, humidity, thermal loads at the various heat sources within the building, thermal properties of the buildings walls and roof as well as air speeds within the subject development for the critical wind angles for each of the seasonal cases investigated. The boundary conditions were accurately determined from wind tunnel measurements.

As temperature heat loading during a day is time dependant, a comparison study was undertaken between the steady state analysis technique (infinite time) and the transient simulation technique, with a 4 hour time period. The comparison between the steady state analysis and 4 hour transient simulations shows very little difference in the internal flow rates and temperatures. A decision was made to base the CFD simulations on the steady state analysis.

Air Quality and Internal Velocity Analysis

To verify the results of the CFD study, further analysis was carried out utilising the results of the wind tunnel study for the development. This was used to verify and ensure that the flow velocities determined from the CFD study at the various openings was accurate as a form of quality assurance. Peddie and Rofail (2011) had previously undertaken full-scale verification of the natural ventilation between wind tunnel modelling results and full-scale performance. Their analysis concluded that there is good agreement between the full-scale measurements and results based on wind tunnel model techniques.

The development consists of three volumes with numerous external openings connected to each volume. The wind driven ventilation between three or more openings in parallel can be determined by determining the internal pressure for the volume linking the various openings. This is obtained by simultaneously equating the flow rate for the various openings using "Equation (1)" while ensuring that the continuity of mass flow is maintained:

$$Q_1 = A_1 C_{d_1} \sqrt{\frac{2(p_1 - p_i)}{\rho}} \qquad (1)$$

$$\sum Q_n = 0 \qquad (2)$$

Whereby Q is the mass flow rate at the opening, A is the openable area of the opening, C_d is the discharge coefficient of the opening and p the mean pressure at the opening and inside the volume considered.

The discharge coefficient for the various openings affects the flow efficiency of the wind entering and exiting the development. These values for discharge coefficient vary depending on the opening type and any proposed obstructions such as louvres and sand traps used to prevent sand propagating into the internal space.

Optimisation of Internal Conditions

The results of the analysis for the initial proposed design of the development indicated that the internal temperatures of the various volumes would significantly exceed the thermal comfort criteria detailed in the earlier sections. Furthermore, there would not be sufficient air changes for the volumes to satisfy even air quality requirements, especially given the use of forklifts and machinery in the internal volumes.

Analysis was carried out for both with wind and without wind scenarios, to account for calm days which occur throughout the year. For the no wind scenario, the natural ventilation was purely driven by the thermal effects with heated air from the machinery within the volumes rising and dissipating out the roof openings.

The issue identified with the initial design was the location of the proposed external openings. The initial design has openings located only over the roof of the volumes, with the various perimeter doorway passages to be kept predominantly closed during operating hours. Further to this, it was noted that due to the prevailing winds for the sites locations, and the current proposed opening locations, the temperatures inside the volumes would actually increase during daily wind events, as opposed to when wind was not considered. This was due to the pressure distribution over the roof openings acting in such a way that they worked against the thermally driven flow previously identified. This therefore meant that the heated air generated by the machinery was not able to escape as easily, instead propagating throughout the space.

Opening Configuration

The prevailing winds of the subject site, needs to be accounted for when considering the positioning of opening locations. This meant the inclusion of openings on the northern, western and southern aspects where possible. The inclusion of openings on the perimeter walls would ensure that a differential pressure could be generated between openings located in different pressure regions. Furthermore, positions openings within the occupiable zone would ensure between ventilation and flow movement would be created throughout the space.

Volume	Air Temperature Range (°C) Existing Design	Air Temperature Range (°C) Additional Openings
Volume 1	36-59	36-53
Volume 2	50-53	36-44
Volume 3	36-37	36-37

Table 1. Effects of Treatments Openings on the Internal Temperatures at 1.5m above the floor (Summer Day)

Additional modelling was carried out with the inclusion of the recommended additional opening locations for the three main volumes of the development. It was noted that for each volume, a significant reduction in the internal temperature could be achieved simply by optimising the opening locations around the development, as detailed in "Table 1". Further to this, the temperature distribution throughout the main volume of the development had also been significantly reduced.

It is however noted that while these reductions of the internal temperatures do not satisfy the previously identified thermal comfort criteria for this climate, there are other significant benefits. The reduction of the internal temperature of the main volumes means that the work required by a supplementary mechanical system to provide suitable conditions to satisfy thermal comfort is largely reduced. Depending on the distribution of the internal temperature and flow patterns, by designing the opening locations to suit to local climate, largely components of the mechanical system could be removed or optimised.

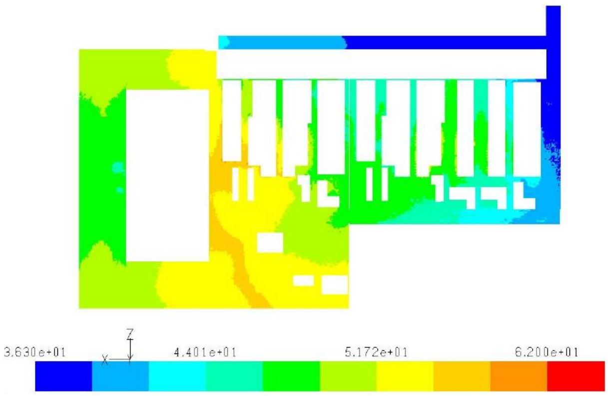

Figure 4. Internal Temperature Distribution of the Original Design (with wind)

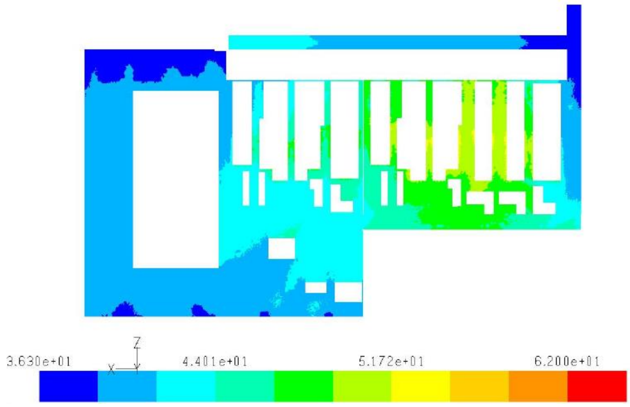

Figure 5. Internal Temperature Distribution with Recommended Additional Openings (with wind)

Conclusion

Natural ventilation is widely used in mild climates, however the benefits of consideration for natural ventilation in more extremely climates is clearly identified. The key aspect is the desired level of amenity that is required by the owner and occupants. For factory type facilities and carparks, when appropriately oriented, natural ventilation in extreme climates can be substantially beneficial. This would be from both an occupant comfort perspective and also from the point of view of energy consumption and mechanical requirements.

With the optimisation of developments to be both more cost effective to construct and also run, the hybrid wind tunnel and computational technique in the modelling of natural ventilation has clearly been shown to be a very beneficial design tool.

References

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