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Indoor Energy Analysis of Food Distribution Warehouse

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Abstract

The current investigation involves carrying out dynamic thermal simulations and computational fluid dynamic analysis (CFD) analysis. The purpose of this analysis is to assist in designing a ventilation system to achieve an acceptable internal thermal environment of less than 28 º C dry bulb temperatures within the occupied space. The thermal performance of the facility over a period of time has been simulated taking into account the effect of thermal mass within the space which affects the average internal space temperatures. Results from the dynamic thermal simulation analysis were then used to provide the boundary conditions for the CFD analysis. The investigated warehouse has been simulated using four different roofs based mechanical ventilation strategies. The amount of goods stored in the warehouse has been found to play a significant role in keeping the warehouse temperature within the acceptable range. An almost empty warehouse tends to vary with the outside ambient temperature. However, a warehouse full of goods makes use of thermal mass to provide a passive cooling strategy. It is recommended that mechanical ventilation of 350 m^3/s of air to be adopted using the smoking fans already exist in the warehouse. These fans should operate when the ambient temperature falls below 27ºC at any time of the day if the temperature requirements are satisfied during the summer period.

Keywords: *Energy Analysis, CFD, Indoor Environment, Ventilation, Thermal Simulation*

1. Introduction

This paper provides details of the thermal performance of a commercial warehouse located in Adelaide, Australia. The warehouse is a large internal space with an average of 13 m high and has a footprint of approximately 40000 m^2. Toward the southeastern corner of the warehouse three storerooms are located, the dangerous goods store, the aerosol store and the confectionary store. The remainder of the warehouse consists of a single area with various types of racks for storage of produce. A central space is provided for sorting and picking goods before being dispatched. Along the majority of the eastern wall are 16 bays for receiving goods. Trucks are reversed into internal receiving bays where they can be unloaded within the building and 31 dispatch docks are located along the western façade, as shown in Fig. 1 [1]. The dynamic thermal simulation has been carried out using the VE-IES software [2]. The analysis utilizes weather data, including wet and dry bulb temperature and incident solar radiation, for a typical reference year (TRY) in Adelaide. This weather data has been recorded at half hourly intervals throughout the TRY and gives accurate data in order to assess diurnal ranges, thermal performance and energy consumption of buildings. The model includes thermal analysis of the various building elements including wall conduction, bulk airflow and shading.

Computational Fluid Dynamics (CFD) is then used to locally investigate the effect of the ventilating system on the air temperature inside the warehouse. Unlike the yearly building performance simulation, the CFD analysis predicts local flow behavior and the resulting air temperature distributions. The CFD simulations use the commercial package CFD-ACE+, which is a robust, commercially available software package designed for complex heat transfer and fluid dynamics applications [3]. CFD is utilized in this project to determine: (a) the effect of the outdoor air conditions on the internal stratification using the baseline ventilation strategy, and (b) the impact of the recommendations from the VE-IES modeling on the conditions within the warehouse.

2. Building Simulation Analysis

The modeling is used to analyze the internal temperature within the warehouse through the selection of appropriate materials. The material selection for this analysis is based upon the information provided from the Architect [1].

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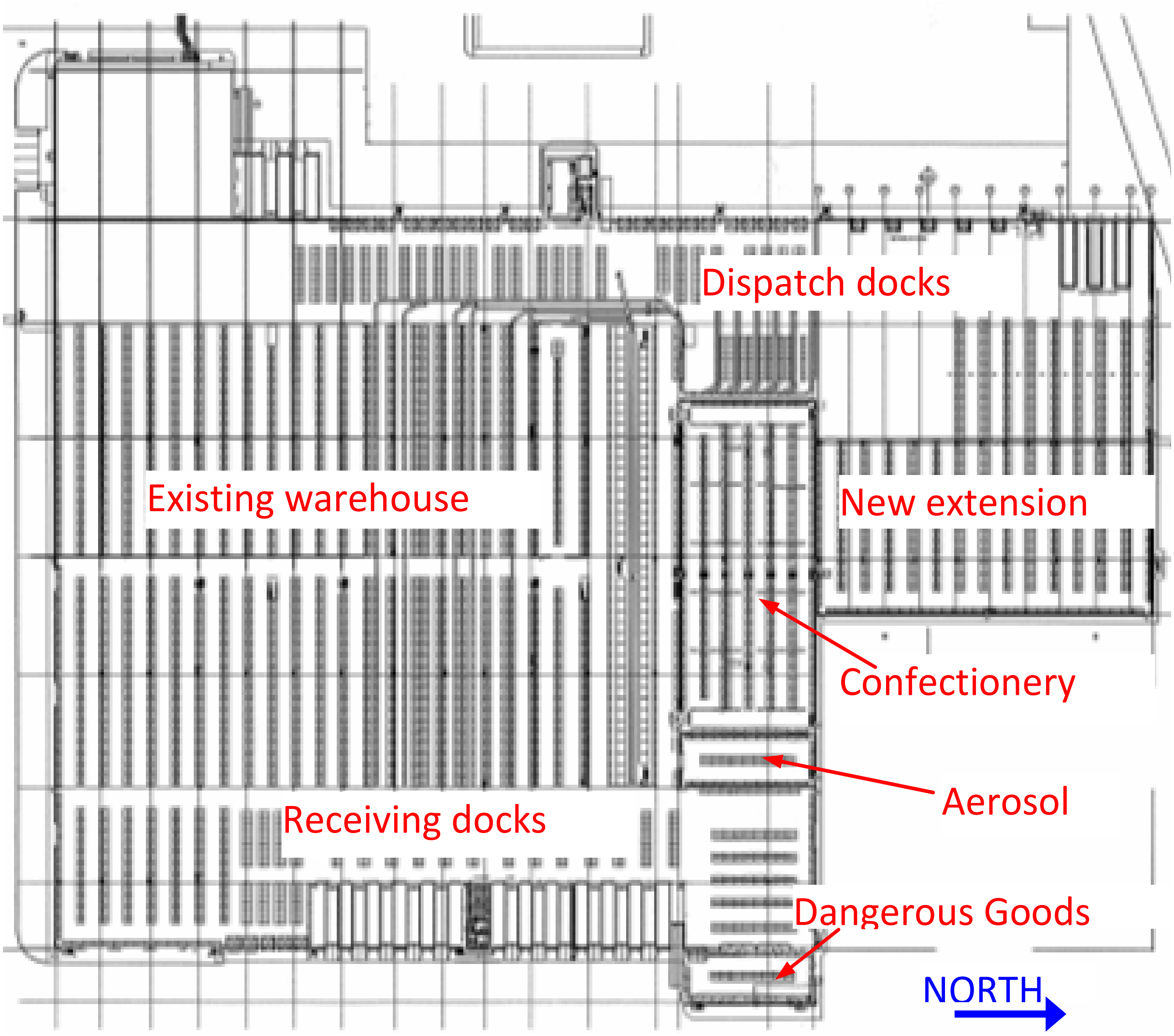


Fig. 1. General view of the warehouse facility.

2.1. Simulation Model

The VE-IES: APACHE software used for the analysis is an advanced dynamic thermal simulation module that is capable of predicting building performance and annual energy consumption in a building. The program is based upon finite difference methods as recommended by CIBSE Part J for energy and environmental modeling to model the transmission and storage of heat in the building fabric [4].

Bulk air movement through infiltration and internal airflow between zones is predicted dynamically as a function of buoyancy. The effects of airflow in and out of the warehouse due to wind, temperature stratification and the ventilation openings are also dynamically predicted.

2.2. Simulation Parameters

The model has been constructed to simulate, as accurately as possible, the environment that will be experienced within the various spaces. The following assumptions have been made for the various option studies [5-9].

Climate

Weather File:	Adelaide
Ground Reflectance:	0.2
Haze Factor:	0.9
Height above Sea Level	43 m
External Temperature:	39.4˚C db
	21.6˚C wb

Internal Casual Gains

Lights:	15 W/m^2
Equipments:	25.5 W/m^2

Occupancy

Sensible:	90 W/person
Latent:	60 W/person
Density:	50 m^2/person

The roof and external wall sections used in the models of the warehouse are based on the construction shown in Figure 2.

Roof

0.48 mm Off-white Colourbond

50 mm R1.2 Insulation

0.1 mm Aluminium foil radiant barrier

External walls

0.48 mm Off-white Colourbond

65 mm R1.5 Insulation

0.1 mm Aluminium foil radiant barrier

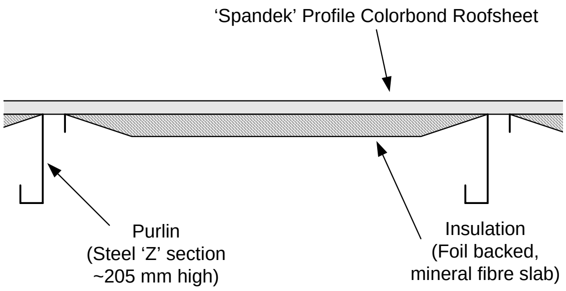


Fig. 2. Standard Roof Construction.

The floor of warehouse is given a thickness of 200 mm cast concrete.

2.2.1. Assumption

The Ambient area is potentially full of a variety of products varying in weight and size. These products have a significant effect on the building's performance due to their thermal mass. The more thermal mass there is in a space the more heat it can absorb and hence delaying the rise in dry resultant temperature for the occupants. The furniture mass factor or Furniture Factor (FF) in the Apache software represents the effect of thermal mass throughout the current study [2]. The reference Furniture Factor utilized in the current study was equal to 11.3 based on the assumption that each of the storage pallets has the following:

Dimensions:	1.2 m x 1.2m x 1.5 m high
Occupancy factor:	60%
Density:	160 kg/m^3
Vertical distribution:	5 pallets

It also has been assumed that all receiving and dispatch docks are open for 10% of the total operating time (24 hrs) at any one time.

2.3. Ventilation Strategies

The ambient space of the warehouse is ventilated naturally and mechanically through the use of the receiving and dispatch docks along the east and west facades and roof mounted smoke fans. The analysis has been performed to determine the dry resultant temperatures achieved within the building based upon the prevailing climate conditions.

Smoke extract fans are located on the roof and are to be used in respect to a night and/or temperature controlled purge strategy of the building when external night temperatures are sufficiently low. The investigated ventilation strategies are:

Option 1: Natural flow due to infiltration which is based on Air Change per Hour (ACH) of 0.5.

Option 2: Exhaust flow rate of 150 m3/s if Tair < 27˚C.

Option 3: Exhaust flow rate of 350 m3/s if Tair < 27˚C.

Option 3a: Exhaust flow rate of 350 m^3/s if T_{air} < 27˚C at night time (8:00 pm till 9:00 am).

Option 3b: Exhaust flow rate of 350 m^3/s if T_{air} < 18˚C, of 0 m^3/s if T_{air} > 28˚C and a linearly interpolated value if (18˚C < T_{air} < 27˚C).

Option 3c: Exhaust flow rate of 350 m^3/s if T_{air} < 24˚C.

Option 4: Exhaust flow rate of 450 m^3/s if T_{air} < 27˚C.

3. Building Environmental Response

The following section outlines results of the analysis using the materials and load profiles outlined in the previous section. The results are displayed in a table and a series of graphs denoting the air, mean radiant and dry resultant temperature of various locations of the internal space against the ambient temperature on the design days.

3.1. Thermal Analysis

Table 1 provides an indication of the air temperatures likely to be achieved within the warehouse at various levels at the design day. It can be seen from the table that the use of mechanical ventilation option has reduced the air temperature inside the warehouse by 1˚C. The slight reduction in the temperature is due to the suction of the relatively cool air from outside the warehouse at night. The purging process reduces the temperature of the different products stored on the shelves, therefore delaying the reaction to the hot air infiltrating into the warehouse on the second day.

Table 1: Maximum air dry bulb temperature inside the warehouse.

(˚C)	Low-Level < 2 m	Mid-Level 2 – 8.5 m	Roof-Level > 8.5 m
Option 1	36.4	36.6	39.7
Option 2	35.8	36.1	38.1
Option 3	35.6	35.9	38.1
Option 4	35.5	35.9	38.1

The reaction of the air temperature of the air inside the warehouse to the air temperature outside the warehouse is shown more clearly in Figure 3 for option 1. The curves in Figure 3 represent the air, dry resultant and mean radiant temperatures in the low-level internal space on the hottest period of the year. The negative effect of having hot outside air temperature for more than one day in sequence is shown clearly. Although the outside temperature on Monday was higher than 30˚C, the inside temperature was less than 28˚C. However, on Wednesday the inside air temperature has almost the same peak as the outside air temperature. Without any purging of the air inside the warehouse, the inside temperature tends to build up and resulting in air temperature higher than 28˚C.

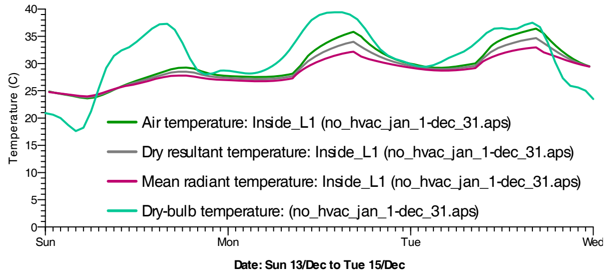


Fig. 3. Dry resultant temperatures at low-level section of option 1.

In order to reduce the air temperature inside the warehouse, a ventilation strategy is needed. Figure 4 shows three different flow rates of air to extract from the warehouse whenever the outside air temperature is lower than 27˚C.

As mentioned earlier, the use of purging strategy is a promising strategy in order to reduce the air temperature inside the warehouse. Although Figure 4 does not show significant improvements in the inside air temperature, it demonstrates the importance of extracting the relatively cool outside air whenever possible to create a thermal lag between the inside and outside air temperatures. It is clear that as the flow rate through the smoking fans increase, the air temperature inside the warehouse tends to lag more behind the outside air temperature. The significance of implementing these ventilation strategies is shown in more details in Figure 5.

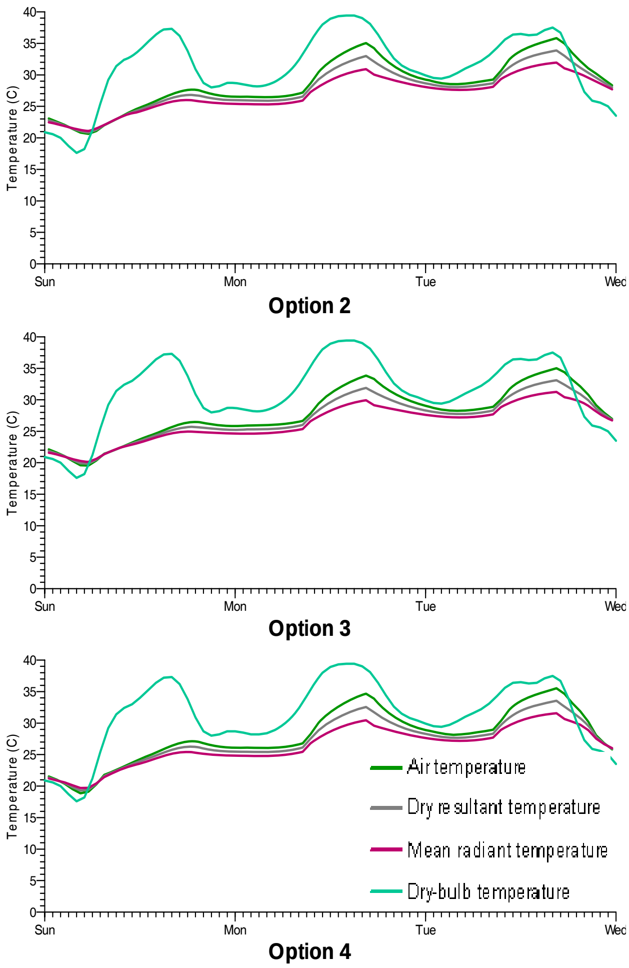


Fig. 4. Dry resultant temperatures at low-level section.

The number of hours for which the air temperature at the low-level inside the warehouse was higher than 28˚C is found to be equal to 589 hrs per year for option 1 as shown by Figure 5. This amount of hours has dropped significantly to less than 251, 197 and 189 hrs for option 2, 3 and 4 respectively. Therefore, a ventilation strategy is necessary for the warehouse in the absence of any air conditioning plant. Due to the small difference between option 3 and option 4, it has been concluded that option 3 has the best amount of airflow rate.

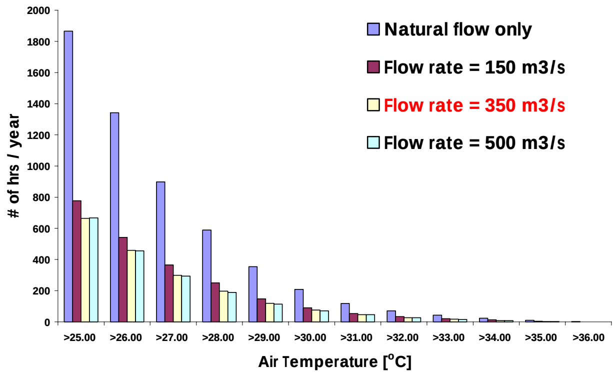


Fig. 5. Dry resultant temperatures at low-level section.

Figure 6 shows the effect of the air temperature at which the purging process starts. It is shown that night purging alone is not the best option. Similarly, purging at lower air temperature has not produced a better temperature performance. This is because the ambient air temperature is on the upper 20s during the hot period of summer in Adelaide. Therefore, setting the reference outside air temperature at 27˚C is the best available option as a ventilation strategy for the current warehouse.

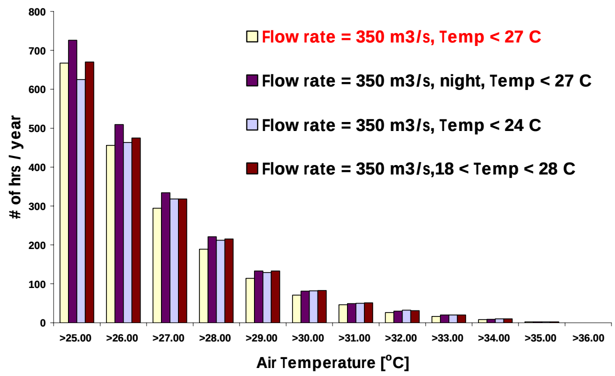


Fig. 6. Effect of ventilation control of ambient air temperature on the inside air temperature at low-level.

3.2. Furniture Factor

The effect of the amount of goods stored inside the warehouse is investigated by simulating different values of the Furniture Factor. Figure 7 shows that as more products stored inside the warehouse, the air temperature inside tends to drop further. For less amount of products stored, the air temperature tends to rise and the ventilation strategy tends to be inefficient.

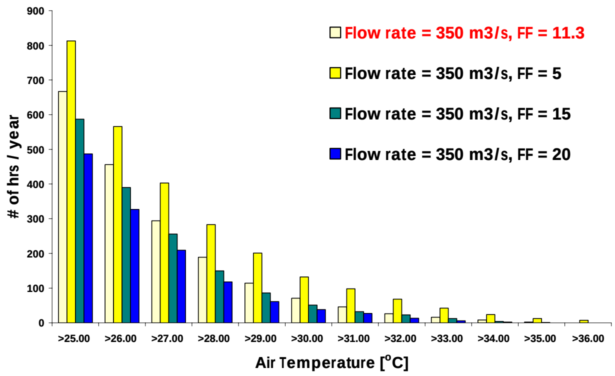


Fig. 7. **Effect of the Furniture Factor on the air temperature at low-level section.**

3.3. Confectionery Room

The previous analysis has been conducted without incorporating any influence of cooled air flowing from the confectionery room into the main space of the warehouse. The main reason behind such an assumption is to produce results with reasonable factor of safety. The air inside the confectionery room has been assumed to have a dry-bulb temperature of 5˚C. In addition, the doors of the confectionery room have been assumed to have the same profile as the doors of receiving and dispatching docks. Figure 8 shows the expected drop in the air temperature inside the warehouse. The number of hrs per year of the inside temperature has dropped from 197 hrs for option 3 to 108 hrs after the inclusion of confectionery room into the calculation.

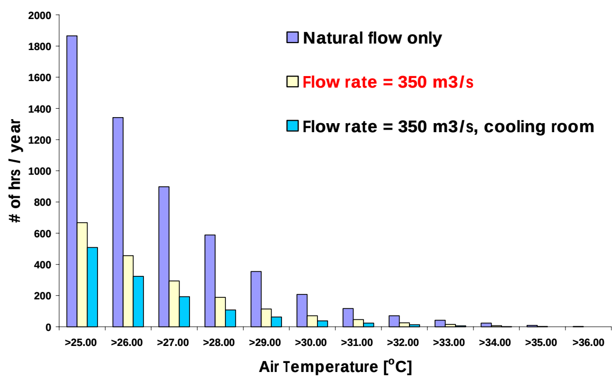


Fig. 8. **Effect of the air exchanged between the confectionery room and main warehouse space at low-level section.**

4. CFD Model

The CFD model is a reduced model of the full warehouse defined earlier by Figure 1 and shown in Figure 9. The section takes an East-West slice through the warehouse that incorporates nine racks. Accuracy of the results is dependent upon the grid resolution used in the model. By creating a model of a representative slice, greater resolution can be achieved and therefore the results will be more accurate. Symmetry planes are used on both sides of the model. The symmetry boundary behaves similar to a wall but assumes no friction and therefore does not influence the flow in the same manner. However, it does mean that the airflow cannot cross the boundary and the flow will be mirrored on the other side of the boundary. The simulation is performed as a steady state simulation, which means that time dependency is not incorporated. Thus, it is considered to be a 'snapshot' in time of the air movement and temperature.

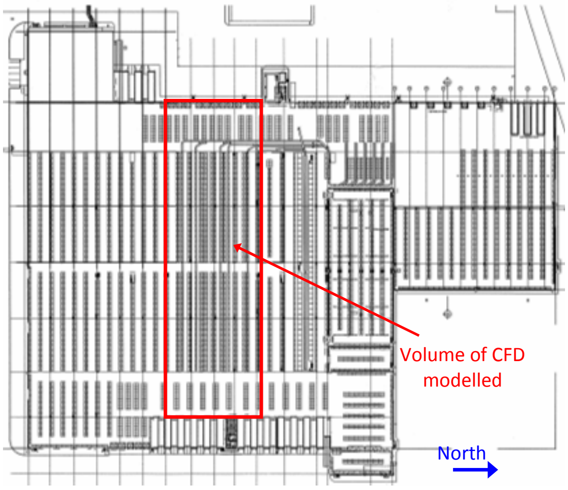


Fig. 9. **Full section of the warehouse for CFD Modeling.**

4.1. Boundary Conditions

The base case is a steady state simulation with boundary conditions defined from weather data for a typical Adelaide year. A summary of the boundary conditions for the current case is presented below whereas the main components of the current model are shown in Figure 10. The recommended ventilation strategy (option 3) has different airflow rate and inlet temperature which are presented as the values between brackets.

Ambient Conditions :

Temperature: 39.4˚C,

Pressure: 101.3 kPa (atmospheric)

Wind: Inflow/Outflow Determined from CFD simulations

Docks :

Receiving walls: Pressure inlet @ 0 Pa(gauge), 35.7˚C

Dispatch walls: Pressure inlet @ 0 Pa(gauge), 35.6˚C

Ambient Inlets :

Receiving doors: Pressure inlet @ 0 Pa(gauge), 39.4˚C (27˚C)

Dispatch doors: Pressure inlet @ 0 Pa(gauge), 39.4˚C (27˚C)

Roof Smoke Fans :

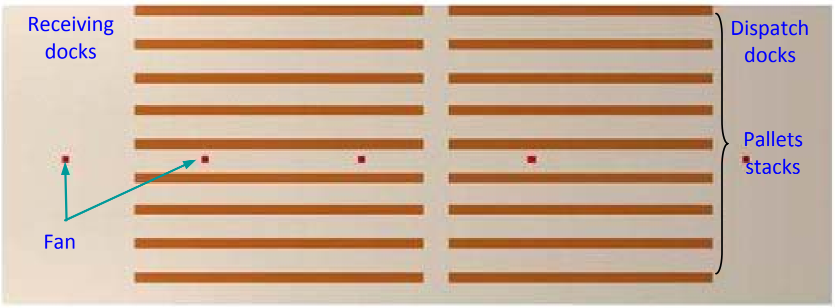
Outlet @ 14.2 m^3/s in total (88.5 m^3/s)

Roof :

Pressure outlet @ 0 Pa(gauge), 39.4˚C

Floor :

Heat flux of 26.1 W/m^2.



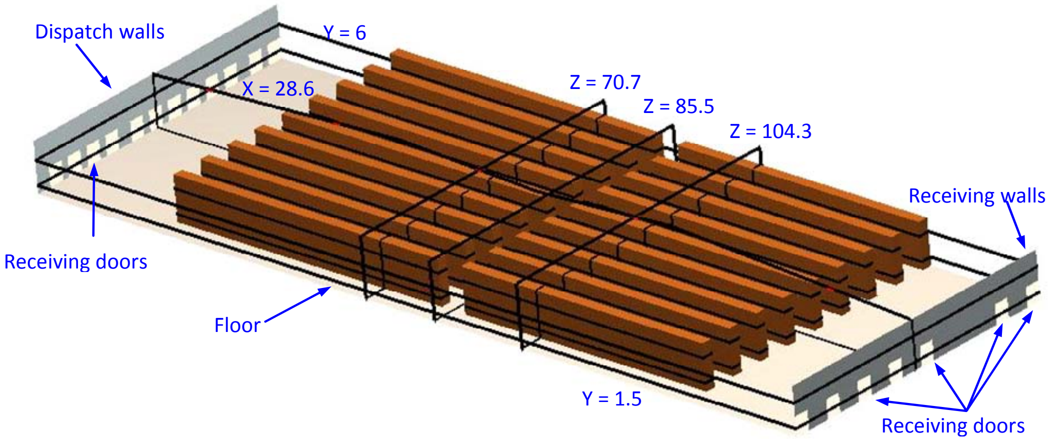


Fig. 10. Full section of the warehouse for CFD modeling with the displaying cuts layout.

4.2. Base Case (Natural Flow Due To Infiltration)

Figure 11 shows the predicted air temperature at different longitudinal positions (z-planes in Figure 10) for the base case. The predicted temperature distributions on the z-cuts are very similar. The stratification of air temperature is evident with air temperature varying from about 32˚C at floor level to above 38˚C under the warehouse roof. The high temperature across the whole warehouse is a result of the combination of high wall temperatures and the high air temperature infiltrating into the warehouse from outside. The low temperature displayed throughout the low-level of the warehouse is the result of the low temperature of the floor. The temperature distribution at a certain height has been found to be less uniform. It is clear that the interaction between the stacks and the adjacent air has enhanced the non-uniformity of the air temperature. However, it is clear that the air temperature at the low-level is significantly less than at the mid-level.

4.3. Recommended Case (Option 3)

It has been concluded from the thermal simulations that option 3 is the best available ventilation strategy for the warehouse. Base on the limiting temperature of 28˚C, a CFD simulation case has been conducted with an outdoor temperature of 27˚C rather than 39.4˚C. The results of the current simulation are shown in Figures 12 to 14. The temperature stratification is similar to the stratification reported for the base case. However, the magnitude of the temperature for the recommended case is significantly less than the temperature for the base case. This is due to the extraction of large quantities of relatively cool air from outside to inside the warehouse.

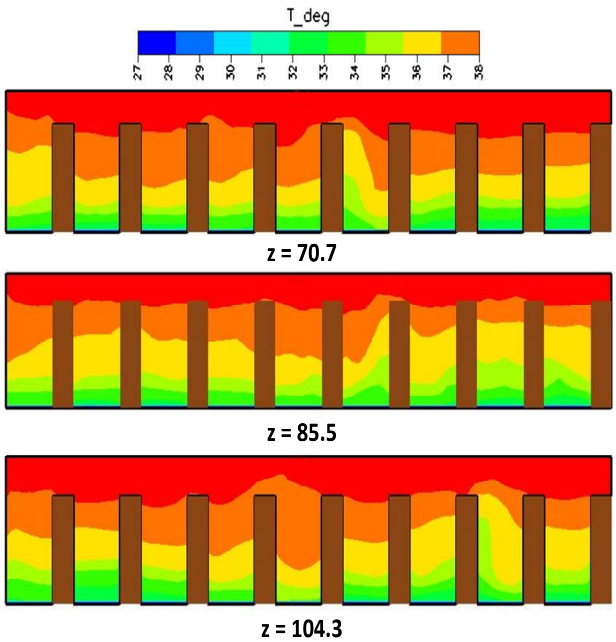


Fig. 11. Base case: stratification in air temperature.

At low-level, the air temperature is well below the 28˚C design requirement. However, the air temperature starts to increase as the height above the ground level increases. Again this increase is due to heat load from the external walls and the stored heat in the pallets. These findings highlight the significance of the ventilation strategy based on the outside air temperature rather than a certain time of a day.

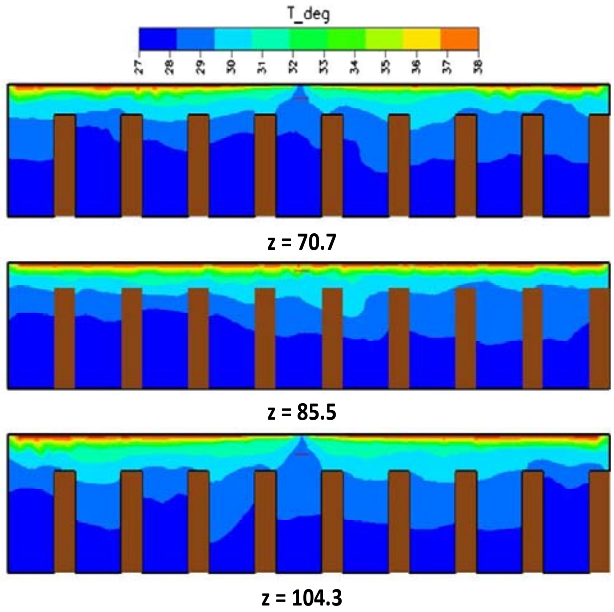


Fig. 12. Recommended case: stratification in air temperature.

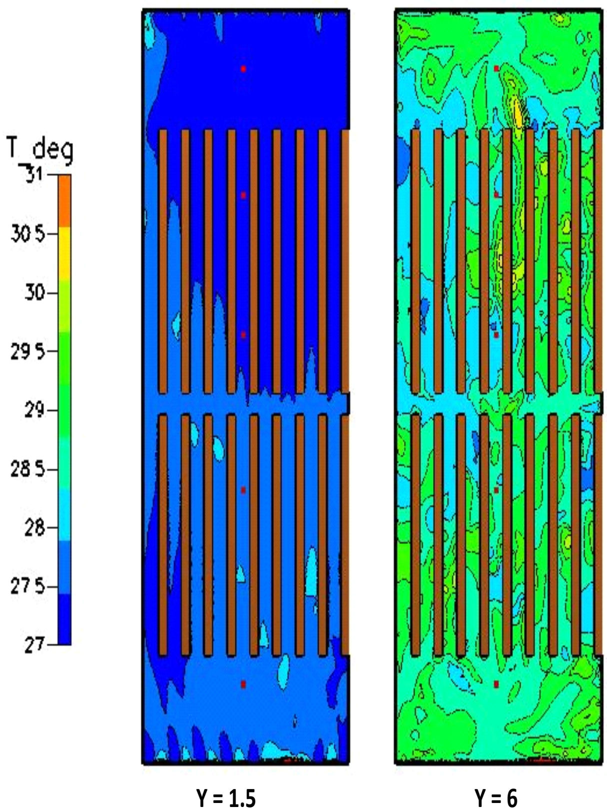


Fig. 13. Recommended case: temperature distribution at different heights.

Although the mechanical ventilation strategy solved the problem of high temperature across the warehouse for a reasonable time across the whole year, the non-uniformity in the air temperature at a certain height is still unsolved. However, such non-uniformity can be contained if the maximum temperature limited to the design temperature value such as 28˚C.

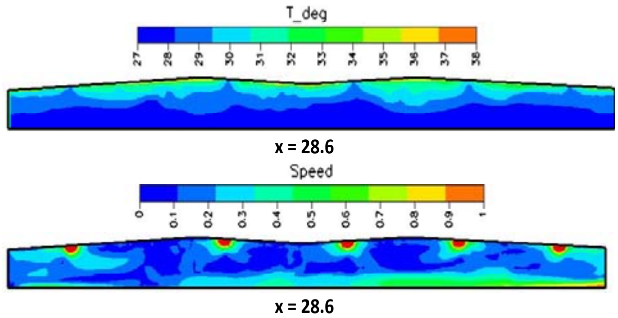


Fig. 14. Recommended case: airflow temperature and speed at the centre plane of the warehouse.

In Figure 12 and Figure 14 above, the stratification of air temperature is clear. The black horizontal line is located at a height of 1.5 m above the floor of the warehouse. At this height, the CFD simulation predicts an air temperature of approximately 35˚C. This is lower than the air temperature predicted in the APACHE modeling and can be explained by:

- The thermal simulation predicts a single averaged temperature across entire zones.
- Infiltration in CFD model is as an overall averaged heat gain, but in thermal simulation, the heat gain is localized, that is, the staging area has a greater heat gain from infiltration than the internal zones.

4.4. Comparison of CFD and Thermal Simulation

When comparing the results of the thermal analysis and the CFD analysis a slight difference in the results modeled is found. The difference is noticeable and consequently has been analyzed to determine the cause.

The main difference is mainly due to infiltration gains in the perimeter zones of the facility. The thermal simulation model calculates the infiltration of hot outdoor air into the perimeter space each hour based on the wind speed and direction data from the typical reference year weather file. The infiltration is higher in the perimeter zones than the internal zones as the façade surface area to volume ratio of the perimeter zones is greater than the internal zones. Consequently the temperatures in the perimeter zones which are separated in the model are elevated in the thermal model.

In comparison the CFD simulation is a static picture of the internal micro-climate. The CFD model represents a single zone of the facility and the infiltration has been treated as an overall average internal heat gain. In reality however, the infiltration heat gains to the perimeter zones such as the receiving or dispatch areas are greater than to the internal areas.

5. Conclusions

The proposed food distribution warehouse in the Adelaide environment has been simulated using four different roofs based mechanical ventilation strategies.

The natural ventilation of the warehouse has resulted in an air temperature higher than 28˚C for a period of 589 hours per year. It has been found that utilizing the smoke fans to extract air into the warehouse is a promising option provided that air only extracted in if its temperature is less than 27˚C.

The amount of goods stored in the warehouse has been found to play a significant role in keeping the warehouse temperature within the acceptable range. It has been found that an almost empty warehouse tends to be sensitive to the outside weather changes. However, a warehouse almost full of goods is a better option in terms of cooling strategy.

The effect of the air flowing from the confectionery room into the main space of the warehouse has been found to be significant. It has lowered the air temperature to lower than 28˚C for a period of 108 hours per year when combined with option 3 ventilation strategy.

6. Recommendations

From both the VE-IES and CFD simulations, it is recommended that:

- Mechanical ventilation of 350 m^3/s of air to be adopted using the smoking fans already exist in the warehouse. The operating temperature of these fans should be fixed at 27˚C of the outside air temperatures. These fans should operate at any time of the day if the temperature requirements are satisfied during the summer period.
- During the hot days of Adelaide summer, an operational time management should be adopted. It is recommended that more traffic through the receiving and dispatch docks to take place in the early morning and night time. However, during the mid-day to late afternoon period it is recommended that traffic be minimized to the minimum possible level.

Acknowledgments

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References

[1] Al-waked, R., Groenhout N., “Woolworths RDC- Gepps Cross, Adelaide: Thermal simulation and CFD analysis,” Bassett Applied Research (BAR), Sydney Report Number 1182_raw_00.doc, September, 2004.

[2] Integrated Environmental Solutions (IES) Ltd, “Thermal Applications Category User Guide- Virtual Environment,” Glasgow-UK, 2004, version 5.4.

[3] CFD Research Corporation, CFD ACE User Manual. 2002. Vol 2-Chapter 12 Numerical Methods. CFD Research Corporation, Cummings Research Park, Huntsville, Alabama, 2002.

[4] CIBSE Guide F, “energy efficiency in buildings.” London, 2004.

[5] ASHRAE, “ASHRAE Handbook: Fundamentals SI Edition,” American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., 2001.

[6] Australian Standards, AS1668.2-1991, “The use of mechanically ventilation and air-conditioning in buildings, Part 2: Mechanical ventilation for acceptable indoor air quality”, 1991.

[7] Australian Standards, AS1668.2 Suppl1-1991, “The use of mechanically ventilation and air-conditioning in buildings, Part 2: Mechanical ventilation for acceptable indoor air quality” (Supplement to AS1668.2-1991), 1991.

[8] Australian Standards, AS1668.2-2002, “The use of mechanically ventilation and air-conditioning in buildings, Part 2: Mechanical ventilation for acceptable indoor air quality”, 2002.

[9] Australian Standards, AS1668.2 Suppl1-2002, “The use of mechanically ventilation and air-conditioning in buildings, Part 2: Mechanical ventilation for acceptable indoor air quality” (Supplement to AS1668.2-2002), 2002.